

The Liquid Argon Calorimeter for the ATLAS experiment at CERN

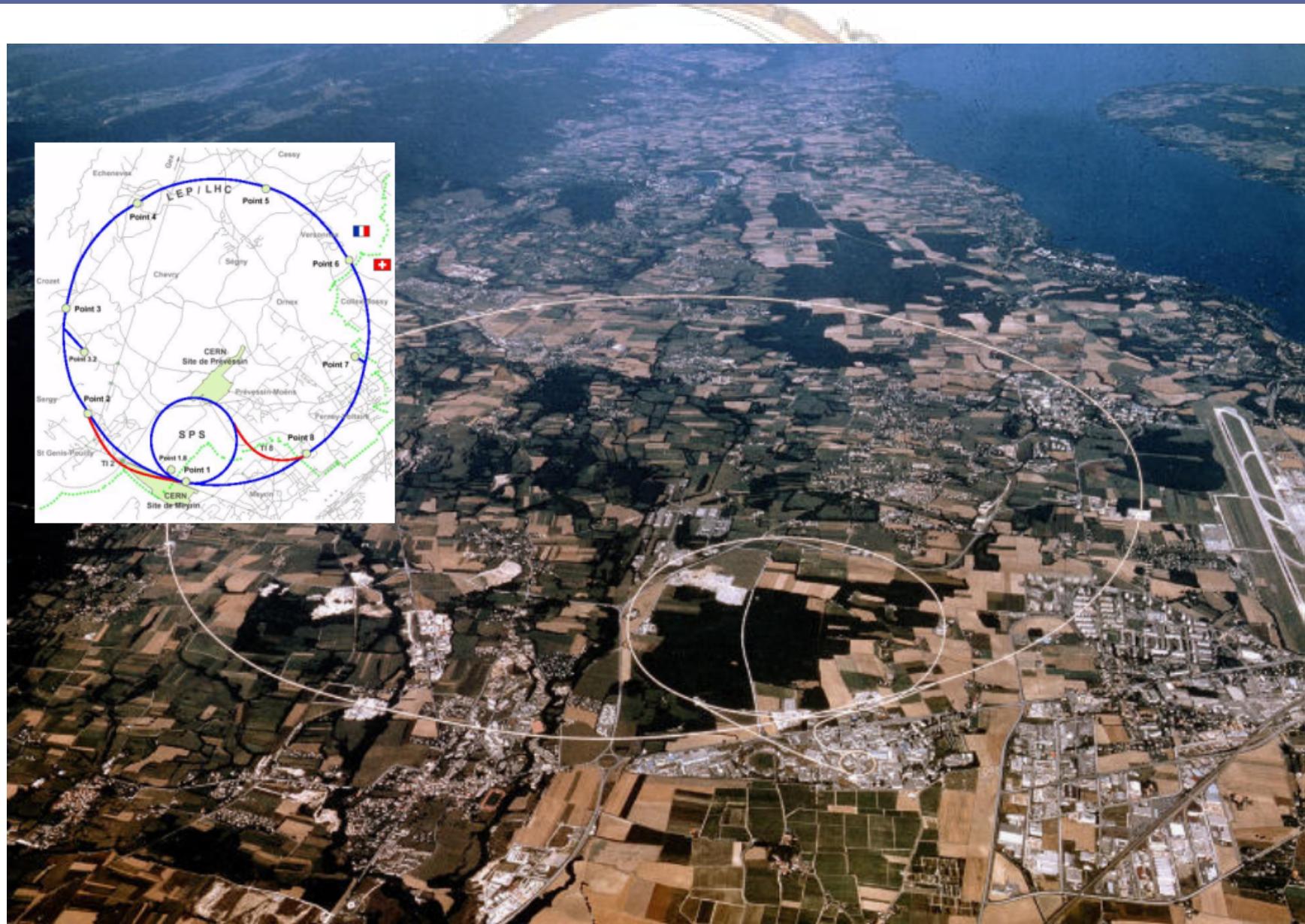
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Outline

- The Large Hadron Collider (LHC) at CERN: Overview
- Physics at LHC
- The ATLAS experiment
- ATLAS Liquid Argon Calorimeters
- The EM Barrel calorimeter
- Readout Electronics
- Performances of the detectors in testbeam
- Status and perspectives
- Conclusions

LHC: Overview



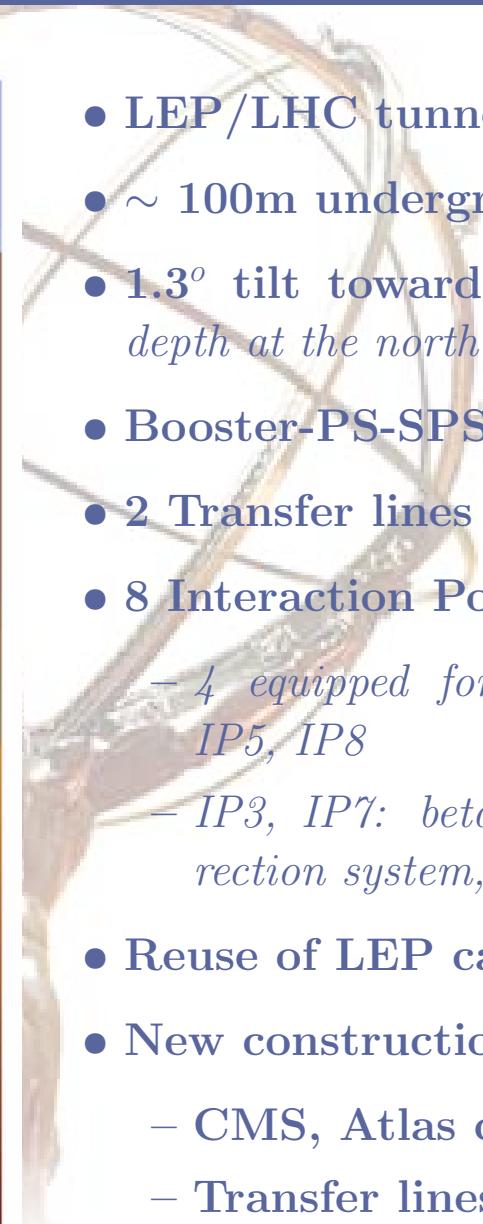
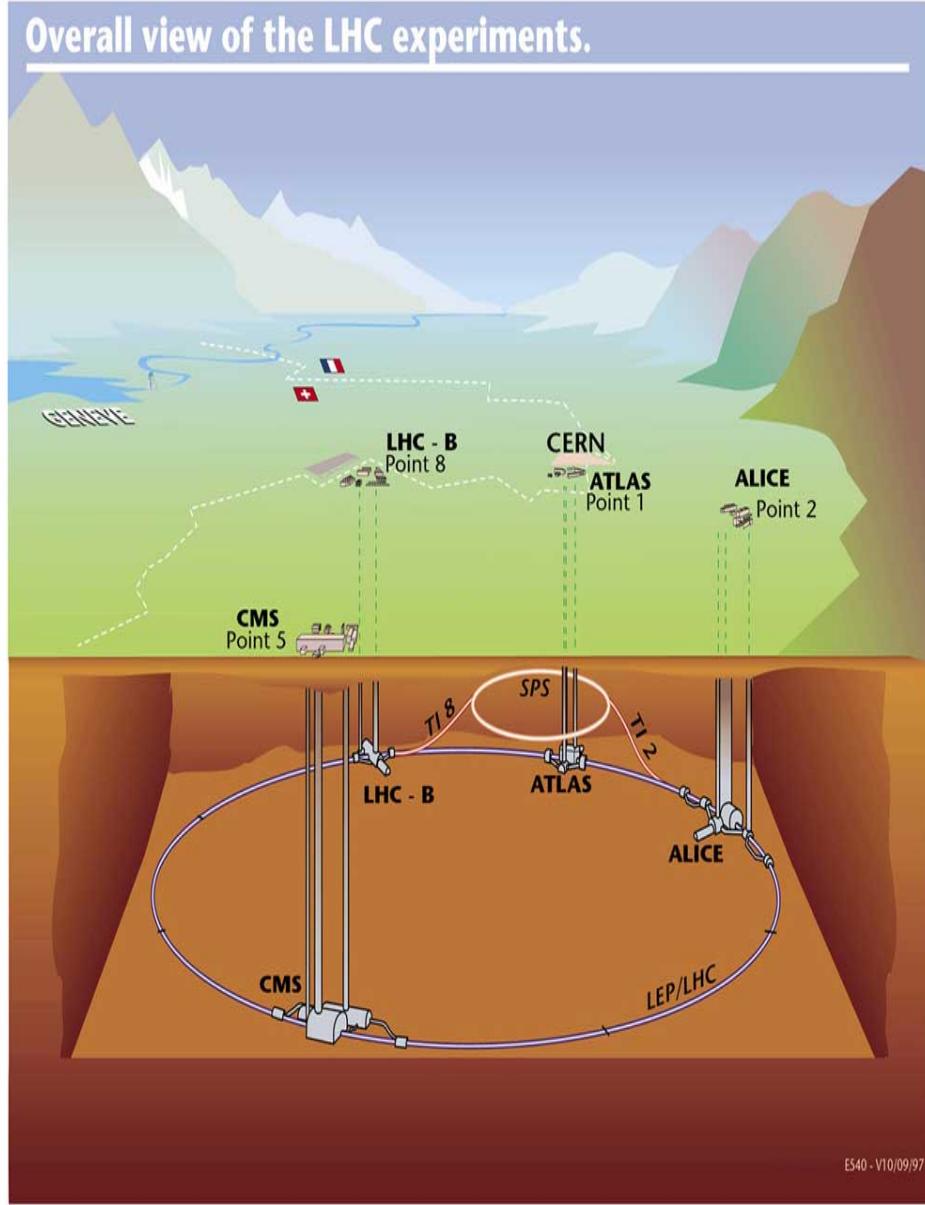
LHC: Overview (2)



- Re-use of the LEP tunnel
- LEP closeout: Nov. 2000
- Last dipole removed: Feb 2002
- 40000 tons removed (*30k from LEP, 10k from the exper. areas*)

LHC: Layout

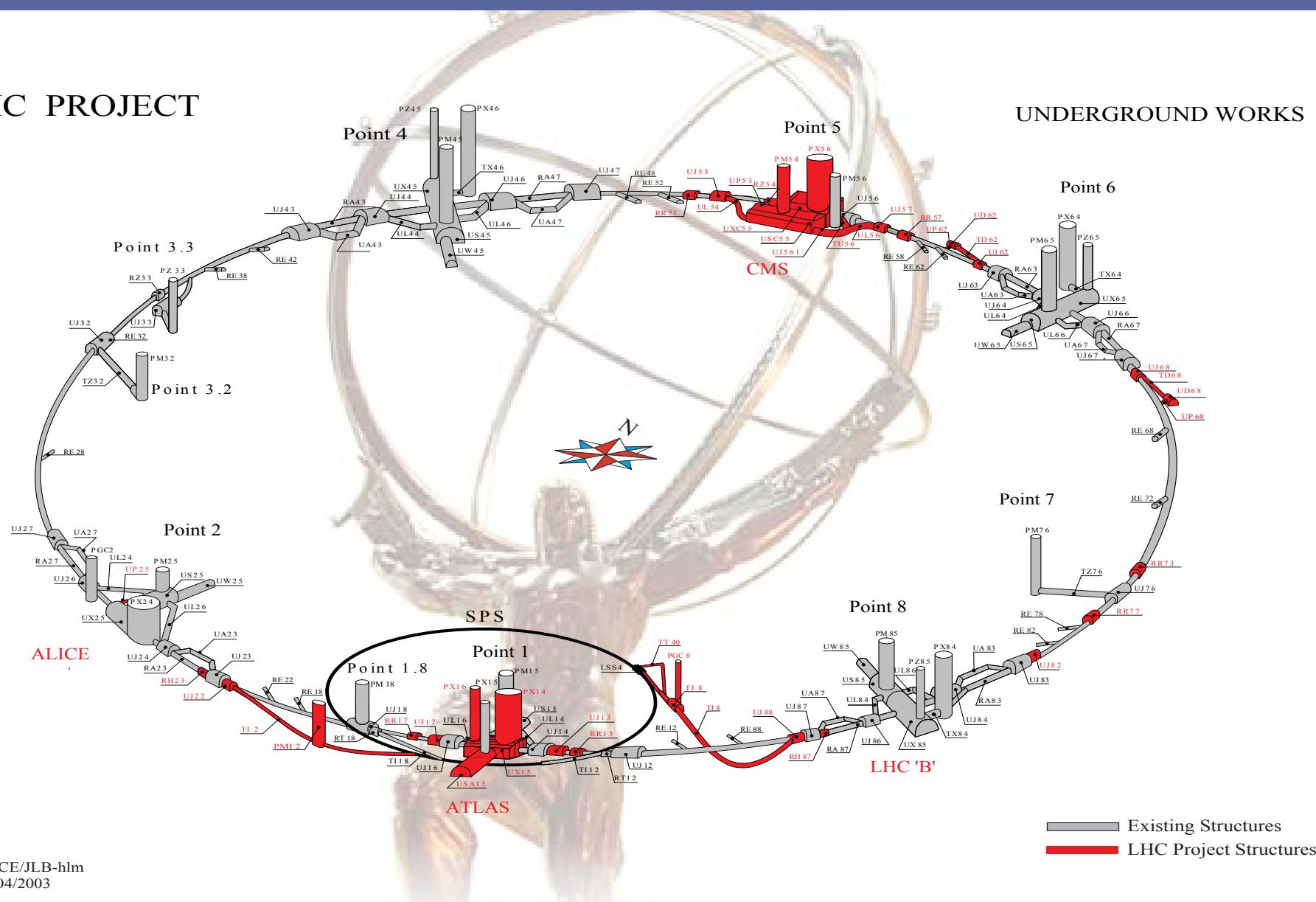
Overall view of the LHC experiments.



- LEP/LHC tunnel: 27km circumference
- ~ 100m underground
- 1.3° tilt towards the lake to reduce the depth at the north side (Jura)
- Booster-PS-SPS as proton injectors
- 2 Transfer lines
- 8 Interaction Points:
 - 4 equipped for experiments (IP1, IP2, IP5, IP8)
 - IP3, IP7: betatron and momentum correction system, IP4 RF, IP6 damping
- Reuse of LEP caverns for Alice/LHCb
- New constructions:
 - CMS, Atlas caverns
 - Transfer lines
 - Beam-Dumping at IP6

LHC: Layout (2)

LHC PROJECT



UNDERGROUND WORKS

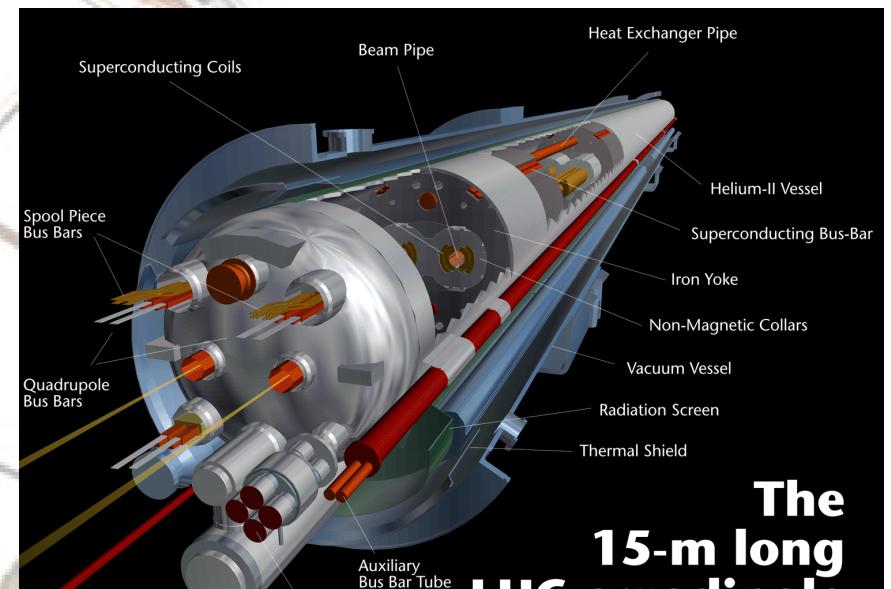
Excavations completed, Atlas cavern delivered (CMS, Jul 2004), all CE for LHC machines completed in summer 2003

LHC: Magnets

- 2 Beam-pipes / 27km circumf.
- 1200 supercond. dipole magnets

L [m]	T _{op} [K]	B _{nom} [T]	I _{nom} [A]	# elem.
14.3	1.9	8.3	11796	1232

- Coils made of Nb-Ti cables
- Dipoles and quadrupoles interconnected so as to form a continuous cryogenic pipe
- Magnets immersed in a Superfluid Helium bath. Low pressure liquid helium heat exchanger
- *Colder than dark outer space (2.7K)*
- In all, LHC cryogenics will need 40,000 leak-tight pipe junctions, 12 Ml of LN₂ will be vaporised during the initial cooldown of 31ktons of material. LHe total inventory 700,000 litres



The
15-m long
LHC cryodipole



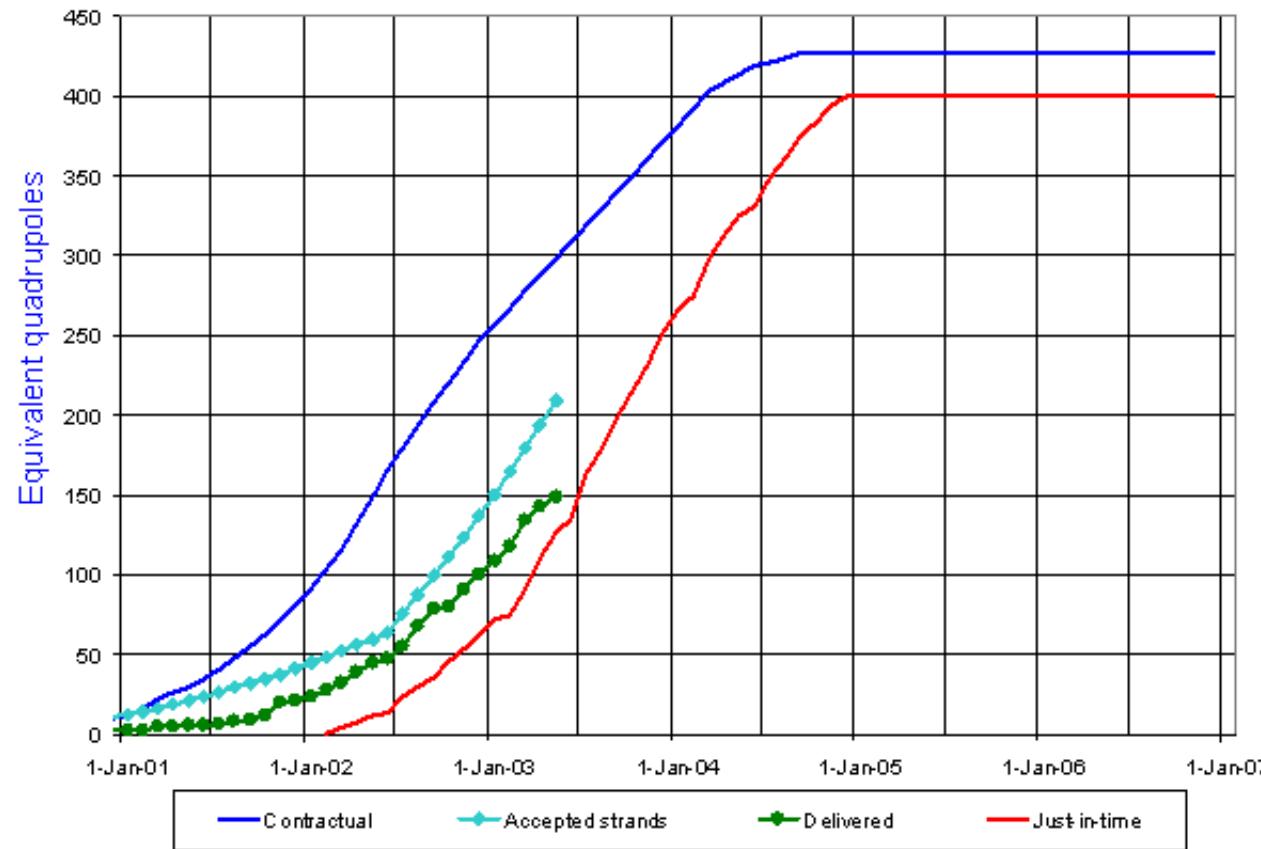
LHC: Magnets (2)



LHC Progress
Dashboard



Superconducting cable 3



Updated 31 May 2003

Data provided by A. Verweij AT-MAS

LHC Parameters: pp-beam



PAC 2003 PARTICLE ACCELERATOR CONFERENCE/May 12-16

Beam Physics at LHC



General Parameters (Protons)

Energy at collision	7	TeV
Energy at injection	450	GeV
Dipole field at 7 TeV	8.33	T
Coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Luminosity	1	E34 cm_s
Beam beam parameter	3.6	E-3
DC beam current	.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Number of particles per bunch	1.1	E11
Normalized transverse emittance (r.m.s.)	3.75	μm
Total crossing angle	300	μrad
Luminosity lifetime	0	h
Energy loss per turn	7	keV
Critical photon energy	4.1	eV
Total radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Filling time per ring	4.3	min

L.R. Evans, CERN EDMS Document No. 381951

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[from L.R. Evans presentation at the 2003 Particle Accelerator Conference, Portland, USA, 12-16 May]

LHC Parameters: A-A beam



PAC 2003 PARTICLE ACCELERATOR CONFERENCE/May 12–16

Beam Physics at LHC



Nominal Lead Ions Parameters

Parameters		Units	Injection	Collision
Energy per charge	E/Q	TeV/charge	0.45	7
Energy per nucleon	E/A	TeV/u	0.18	2.76
Centre-of-mass-energy	E _{cm}	TeV	73.8	1148
Dipole field	B _{max}	T	5.391	8.386
Transverse normalized emittance	□*	□m	1.5	1.5
□ at IP	□*	m	10	0.5
r.m.s. beam radius at IP	□*	□m	280	16
Crossing angle		□rad	< 100	< 100
Longitudinal emittance	□*I	eVs/charge	1	2.5
r.m.s. bunch length	□ _s	cm	11.5	7.5
r.m.s. energy spread	□ _E /E	10 ⁻³	0.468	0.114
Bunch spacing	I _b	ns	100	100
Bunch harmonic number	h _b		891	891
Number of bunches per ring	n _b		592	592
Filling time in the LHC		min	9.8	-
Number of ions per bunch	N _b	10 ⁷	7.0	7.0
Number of ions per beam	N	10 ¹⁰	4.1	4.1
Ion intensity per beam		mA	6.1	6.1
Initial luminosity per bunch		10 ²⁴ cm ⁻² s ⁻¹	-	1.7
Total initial luminosity	L ₀	10 ²⁷ cm ⁻² s ⁻¹	-	1.0
IBS emittance growth		h	7.5	15
Luminosity half-life		h	-	4.2

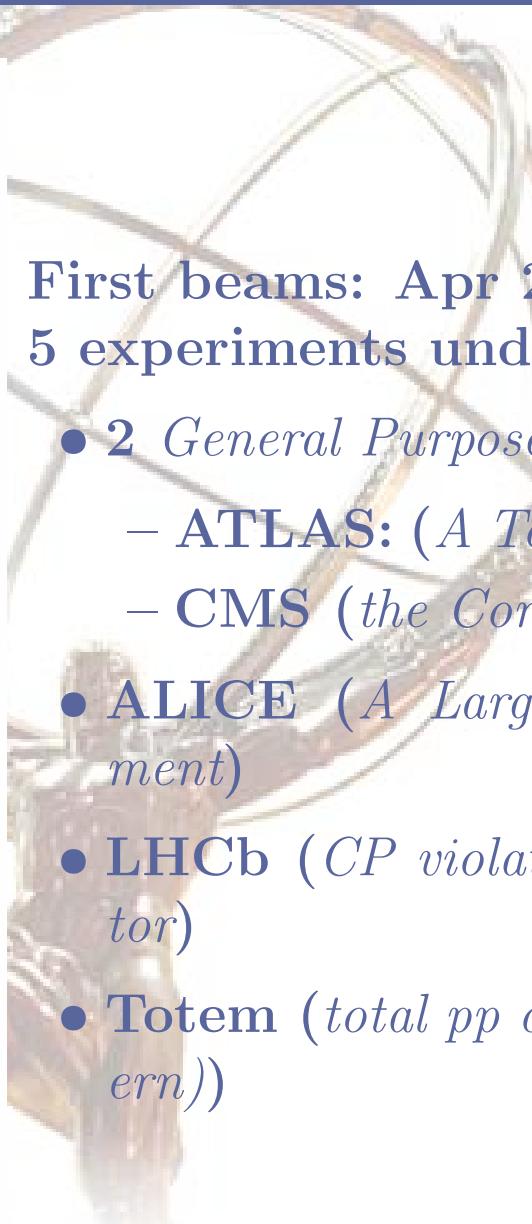
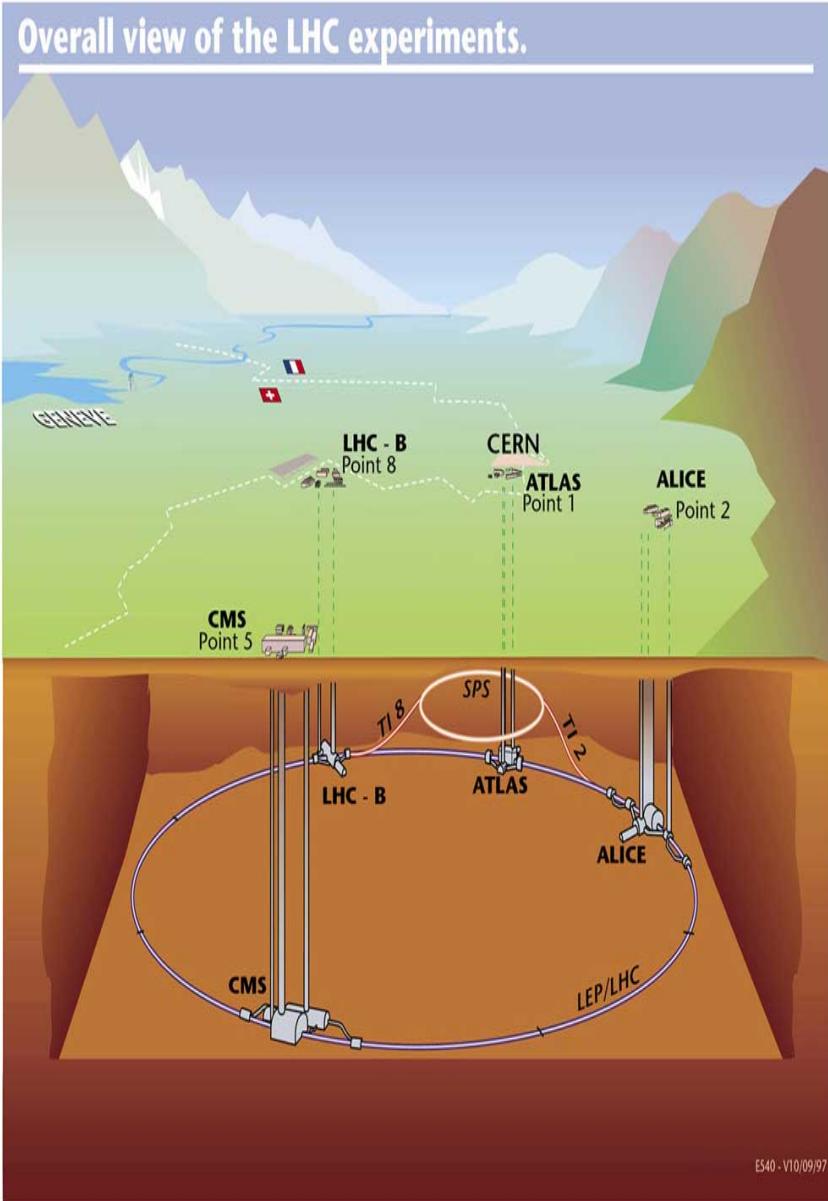
L.R. Evans, CERN EDMS Document No. 381951

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[from L.R. Evans presentation at the 2003 Particle Accelerator Conference, Portland, USA, 12-16 May.]

LHC experiments

Overall view of the LHC experiments.



First beams: Apr 2007
5 experiments under construction

- 2 General Purpose experiments:
 - **ATLAS**: (*A Toroidal LHC Apparatus*)
 - **CMS** (*the Compact Muon Solenoid*)
- **ALICE** (*A Large Ion Collider Experiment*)
- **LHCb** (*CP violation in the b-quark sector*)
- **Totem** (*total pp cross-section (CMS cavern)*)

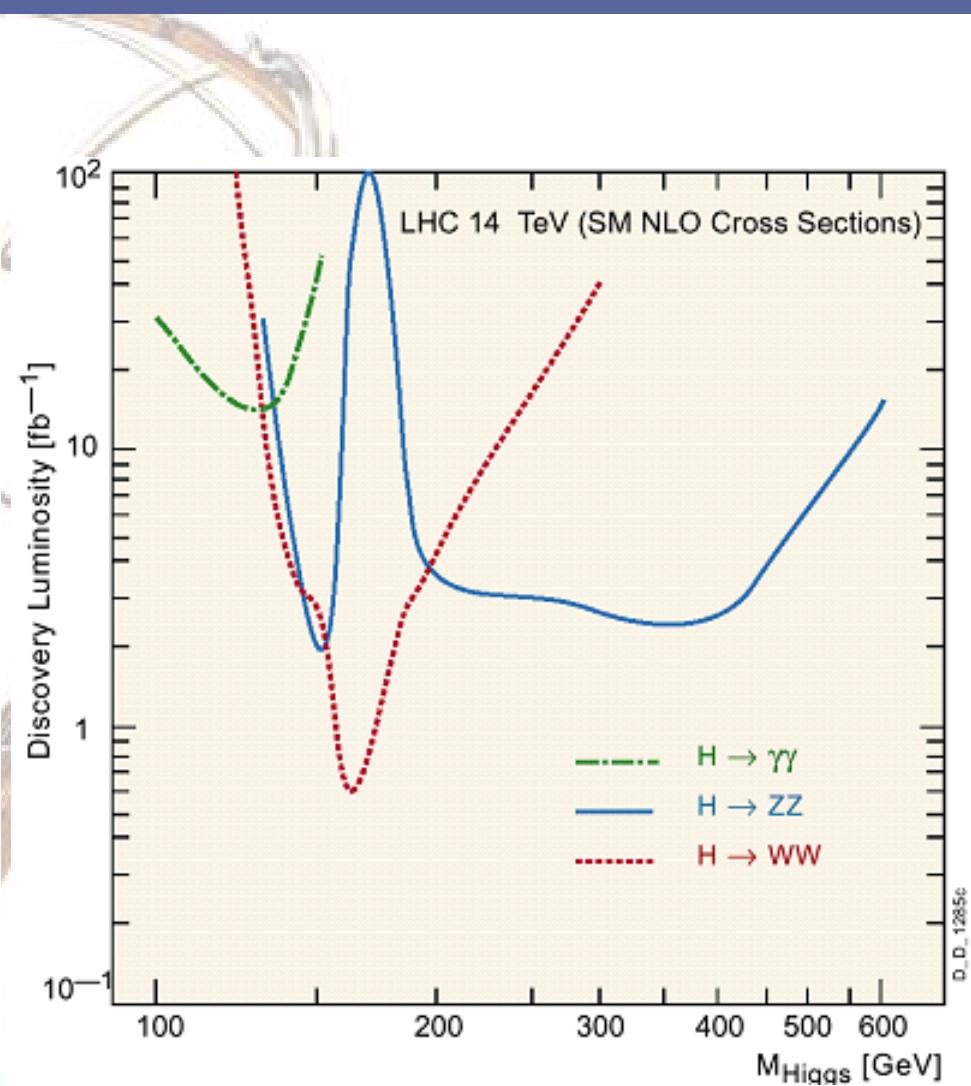
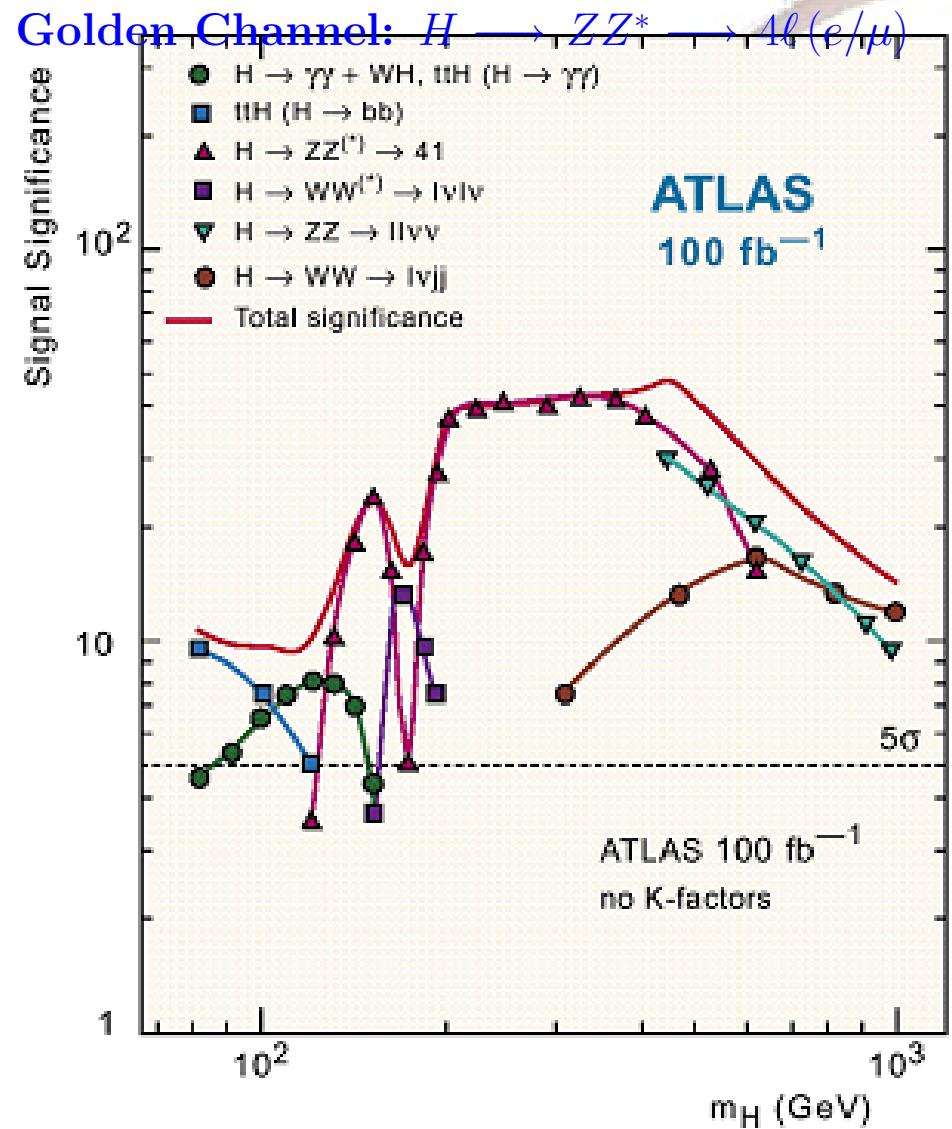
LHC Physics Topics(2)

LHC capability to discover new physics or simply verify current theories is unprecedented. Even during the 1st year of running ($L = 2 \cdots 10^{33} \text{cm}^{-2}\text{s}^{-1}$) with an integrated luminosity of 10fb^{-1}

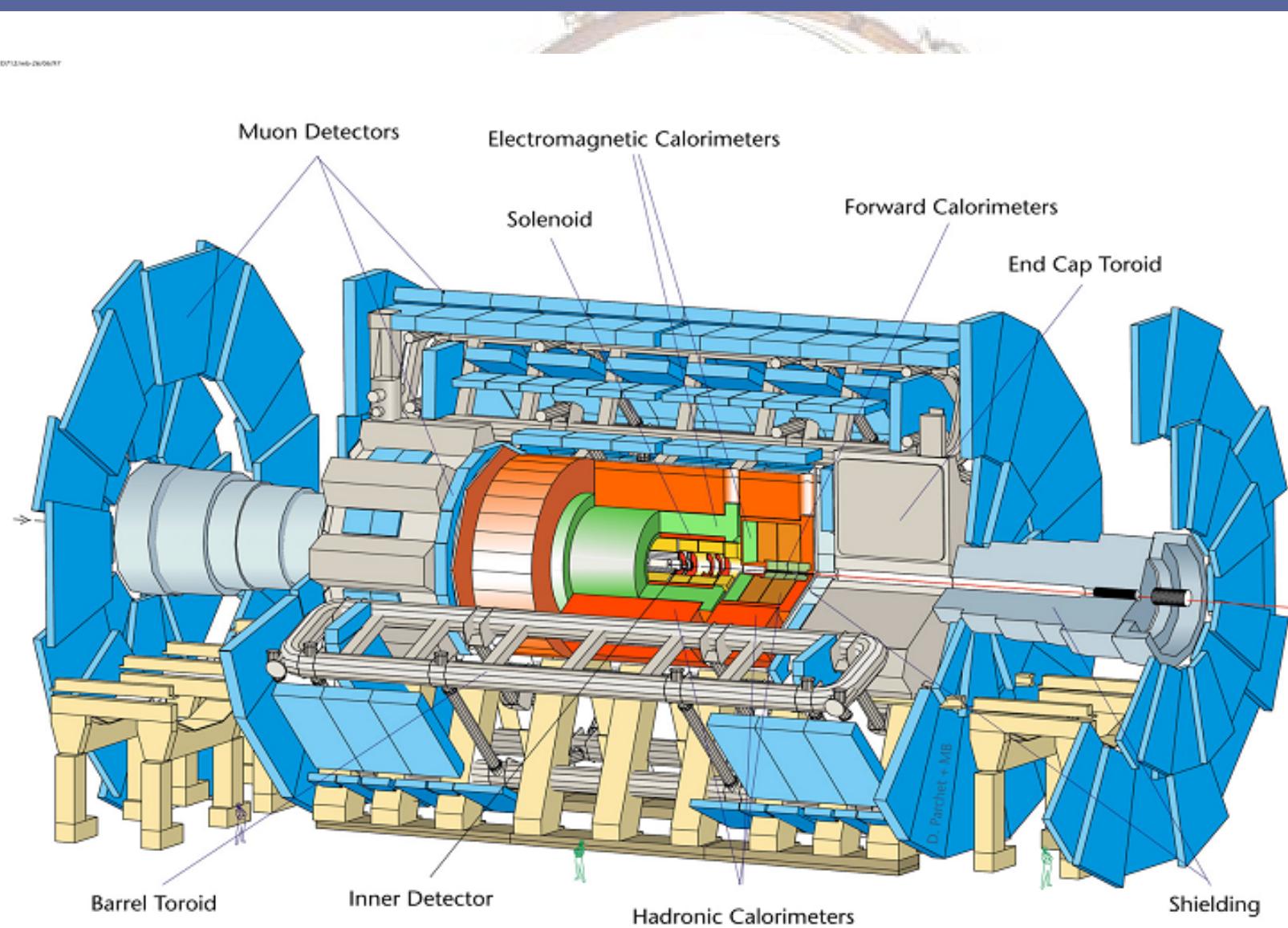
Process	Rate	# Events	Total statistics collected at previous machines by 2007
$W \rightarrow e\nu$	30	10^8	10^4 LEP / 10^7 Tevatron
$Z \rightarrow ee$	3	10^7	10^7 LEP
$t\bar{t}$	2	10^7	10^4 Tevatron
$b\bar{b}$	10^6	$10^{12}-10^{-13}$	10^9 Belle/BaBar
H (m=130GeV)	0.04	10^5	?
$\tilde{g}\tilde{g}$ (m=1TeV)	0.002	10^5	—

- Electroweak Symmetry Breaking, Higgs Boson
- Supersymmetry
- New Particle Search
- Extra-dimensions
- top/bottom
- Heavy Ion

LHC Physics Topics(3)



Atlas: Detector Overview



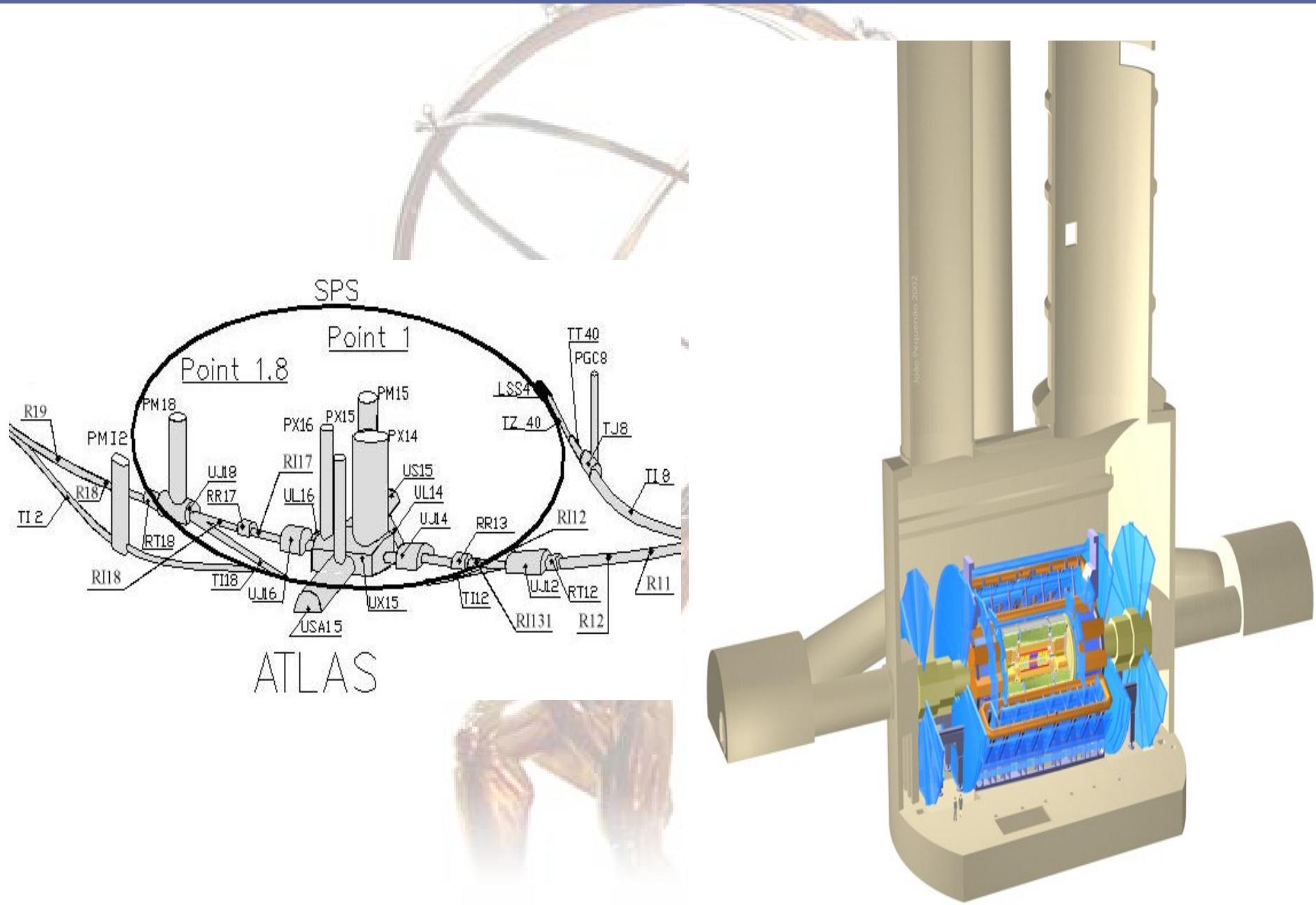
Diameter 25mt, Barrel Toroid length 26mt, Weight 7000 tons

Atlas: Detector Overview (2)



... as tall as a 5 stories building

Atlas: Installation/Pit



Atlas: Civil Engineering

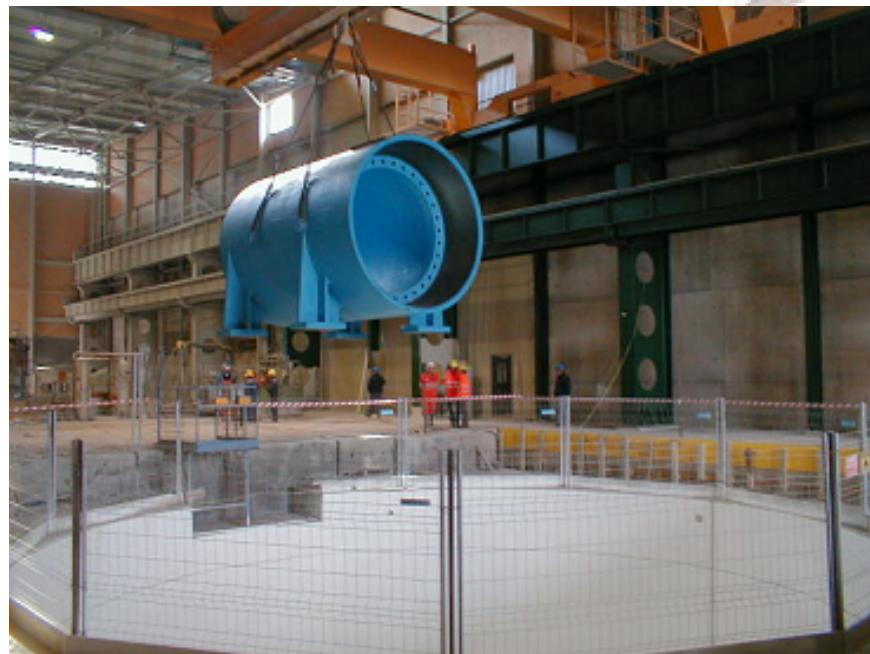


LHC Point 1 - UX 15 Cavern - General view - 20-03-2003 - CERN ST-CE

Atlas: Civil Engineering (2)



Atlas: Civil Engineering (2)

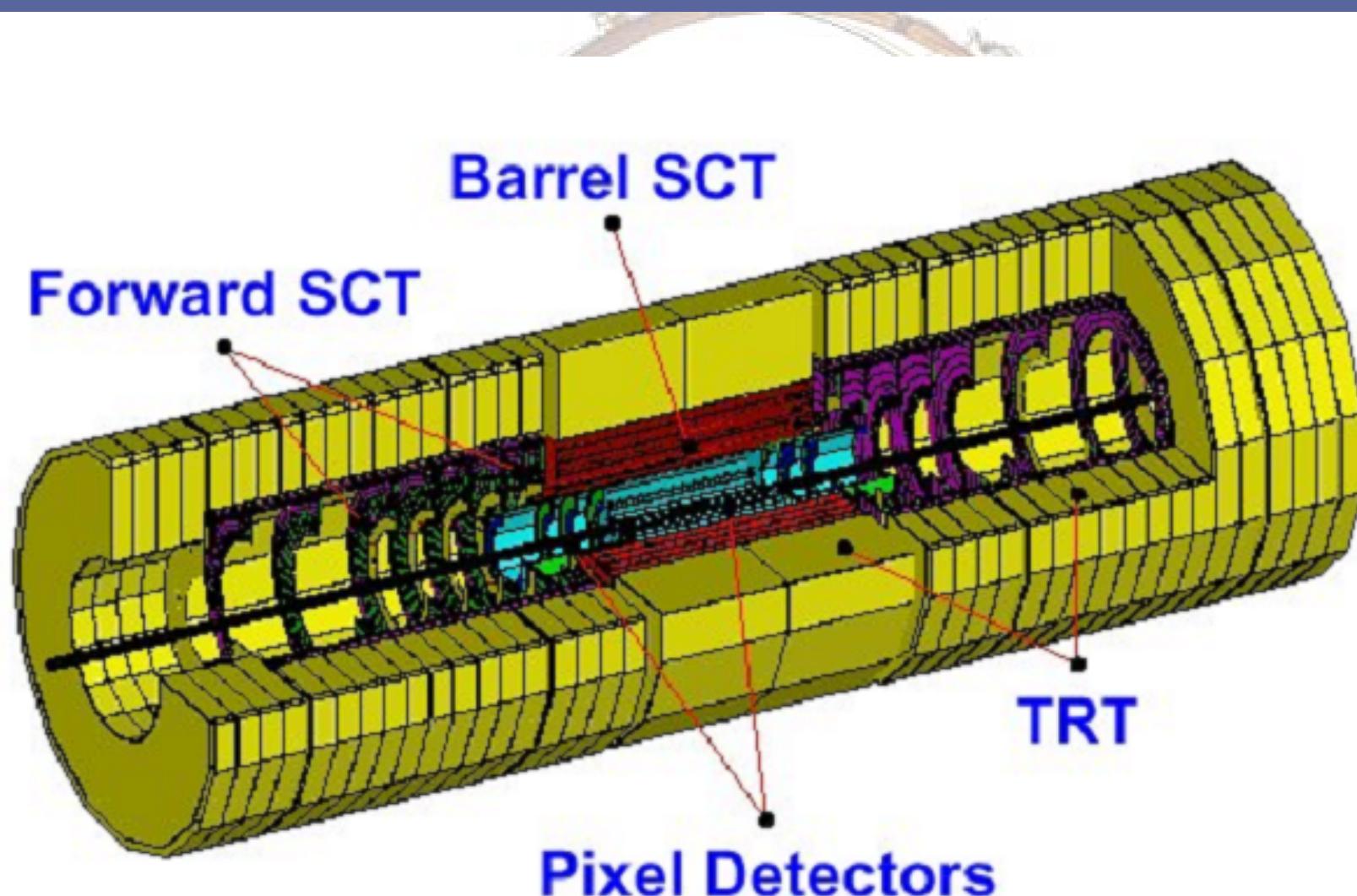


- Installation of TX1S shield beg. April
- BNL Instrumentation Division Seminar - Jun 11th, 2003- pag. 19

Atlas: Inner Detector

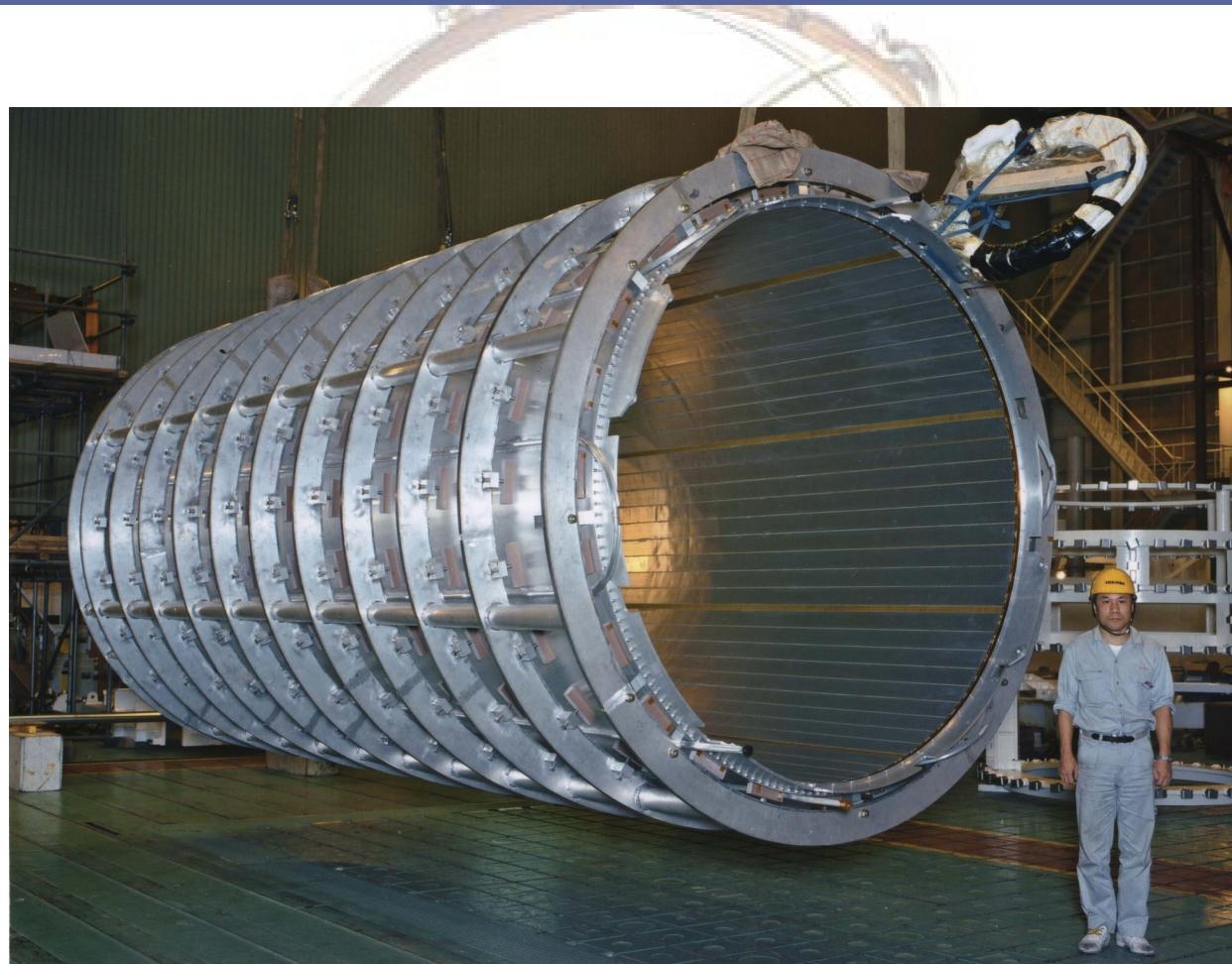


Atlas: Inner Detector



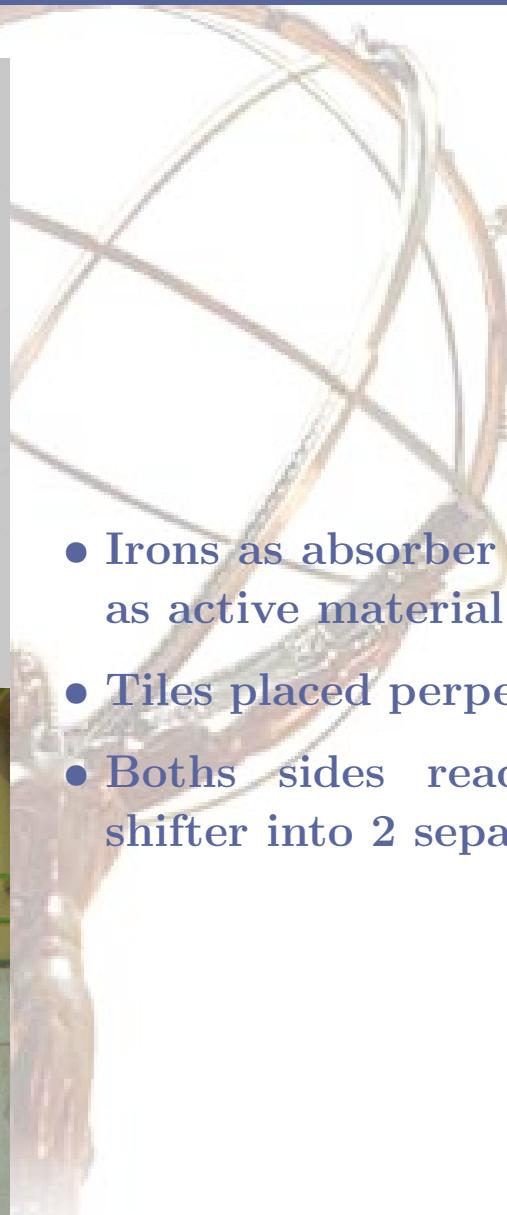
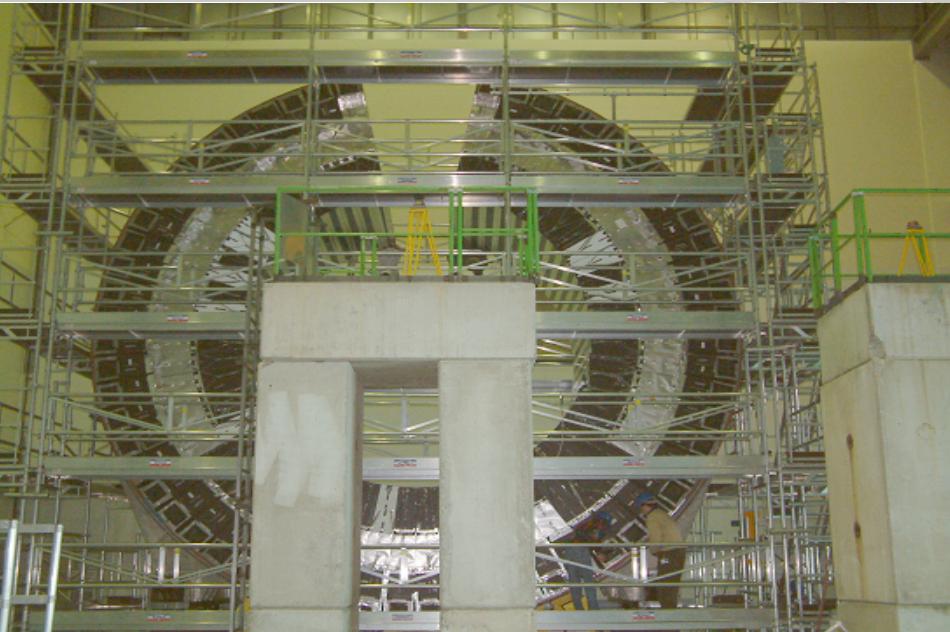
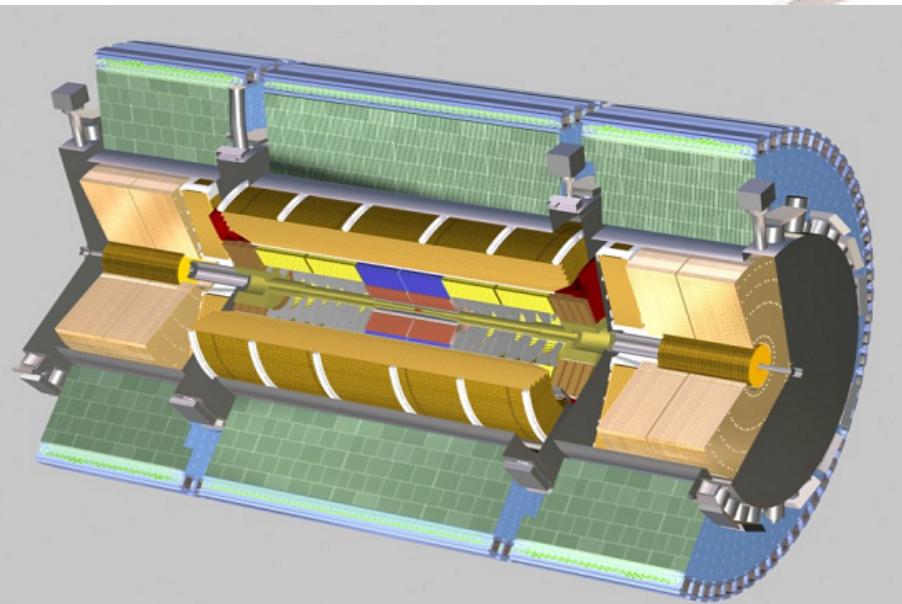
- Silicon Pixels: 3 barrel layer modules + 3*2 disk modules
- Silicon Tracker
- Transition Radiation Tracker (straw tubes with Xe/CO₂/O₂ mixture)

Atlas: Superconductive Solenoid



- Field: 2T, Energy Stored: 38MJ
- Fully tested
- Ready for integration in the barrel EM cryostat by end of 2003
- Cryogenics chimney tested in summer 2002

Atlas: Tile Calorimeter

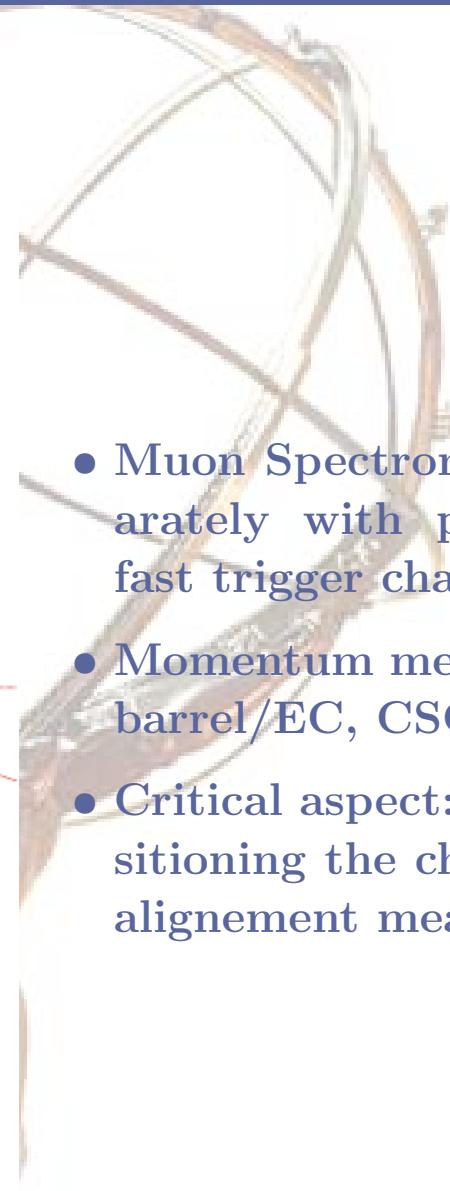
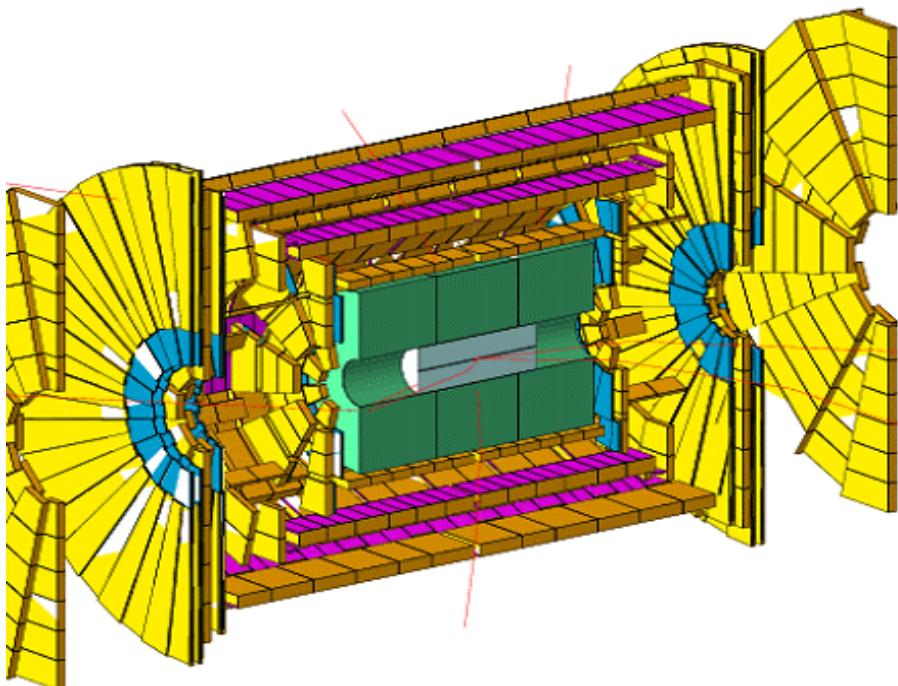


- Irons as absorber and scintillating tiles as active material
- Tiles placed perpendicular to the beam
- Both sides readout by wavelength shifter into 2 separate PMs

Atlas: Toroids

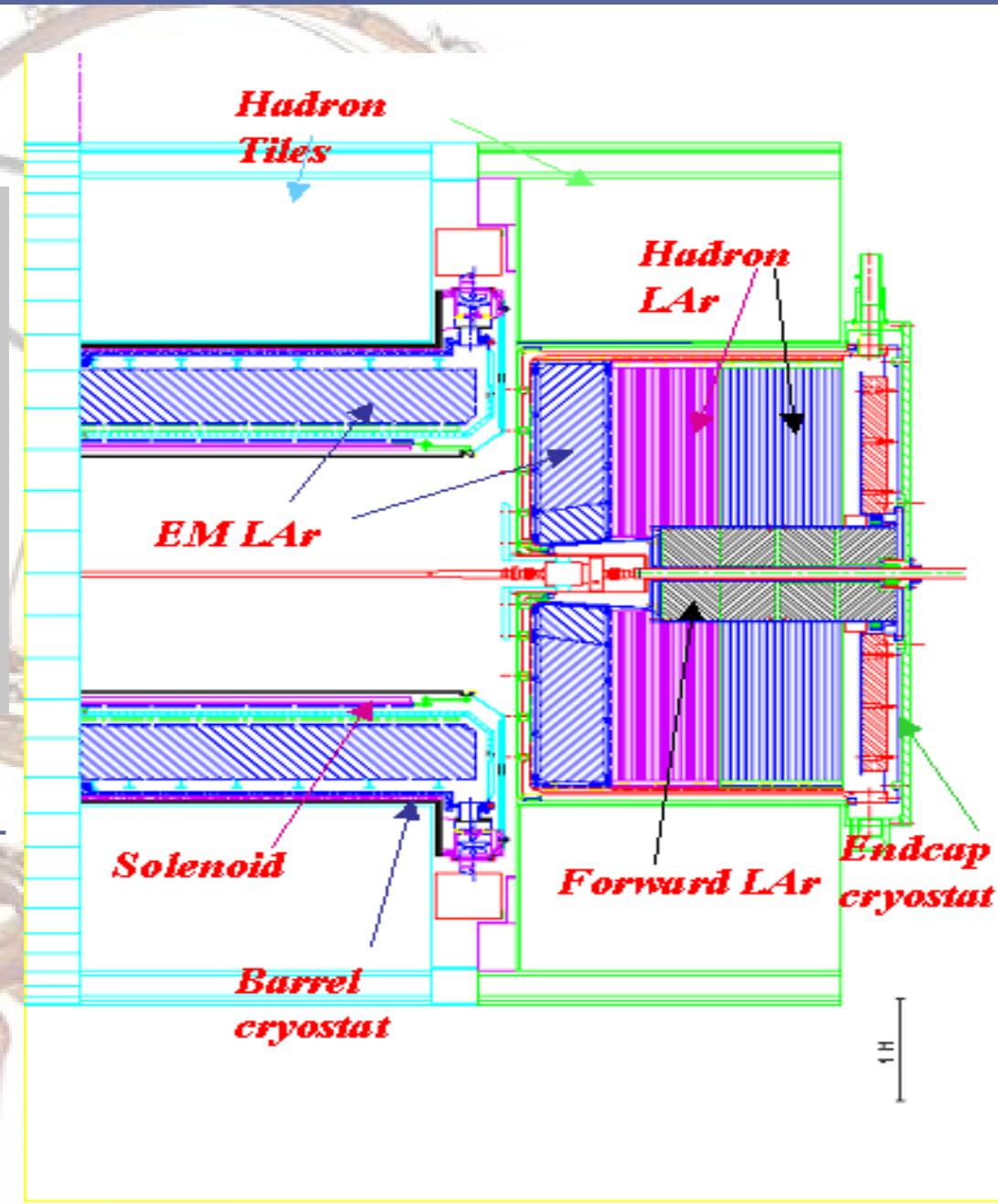
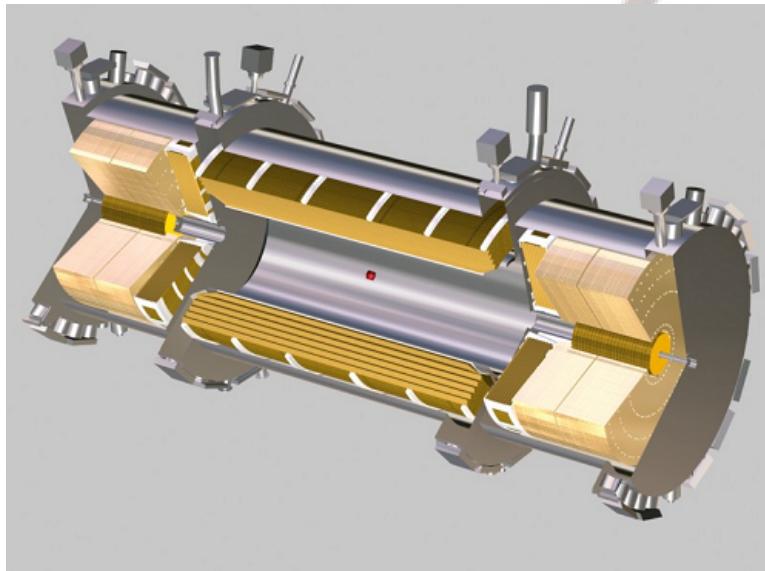


Atlas: Muon Spectrometer



- Muon Spectrometer instrumented separately with precision chambers and fast trigger chambers (
- Momentum measurement: MDT in the barrel/EC, CSC in the forward region
- Critical aspect: accuracy needed in positioning the chambers and sofisticated alignment measurement

Atlas: LAr calorimeters



- EM barrel and EC: “accordion” geometry
- Hadronic Endcap
- Forward Calorimeter

LAr EMB: Calorimetry requirements

- Rapidity coverage
- Energy Range (16 bits):
 - Pileup noise in single readout cell: $\sigma \simeq 50\text{MeV}$
 - No significant degradation from readout electronics
 - Z^* reconstruction ($M \simeq 5\text{TeV}$) sets the upper limit on the energy to be measured in a readout element

- Absolute em energy scale/linearity *0.1% for W,top mass measurement*
- Energy Resolution:

$$\frac{\sigma}{E} = \frac{a [\%]}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Stochastic term: $a \leq 10\%$
- Noise term ($b \leq 200\text{MeV}$)
- Constant term ($c \leq 0.7\%$)

$H \longrightarrow \gamma\gamma$: $\sigma_{m_H} \simeq 1\%$

LAr EMB: Calorimetry requirements (2)

- Angular Resolution

$$\sigma_\theta \leq \frac{50\text{mrad}}{\sqrt{E(\text{GeV})}}$$

resolution affects the accuracy on H mass reconstruction

- γ reconstruction and direction measurements: fine η granularity of the first sampling layer + presampler

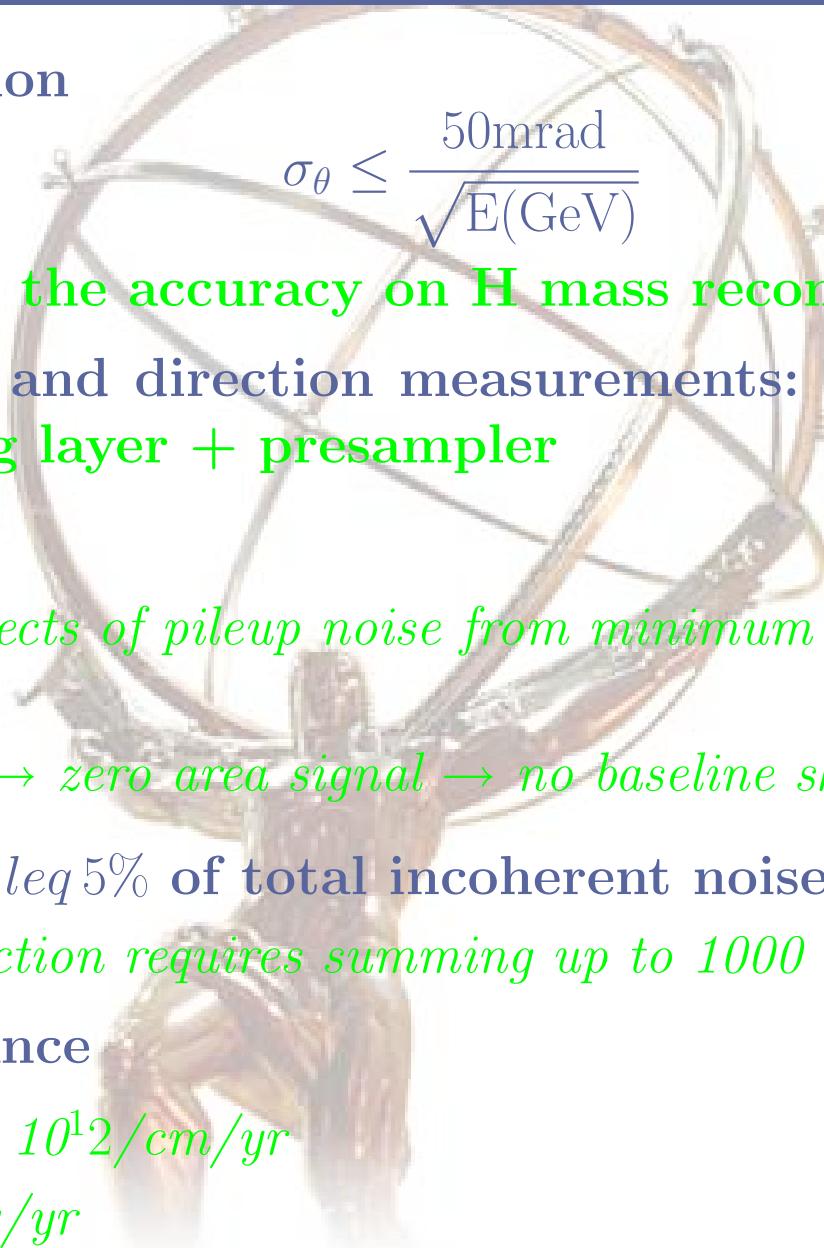
- Fast Response:

- minimize the effects of pileup noise from minimum bias events through fast shaping
 - bipolar shaping \rightarrow zero area signal \rightarrow no baseline shift from pileup

- Coherent Noise: $leq 5\%$ of total incoherent noise per channel
jet and τ reconstruction requires summing up to 1000 cells

- Radiation resistance

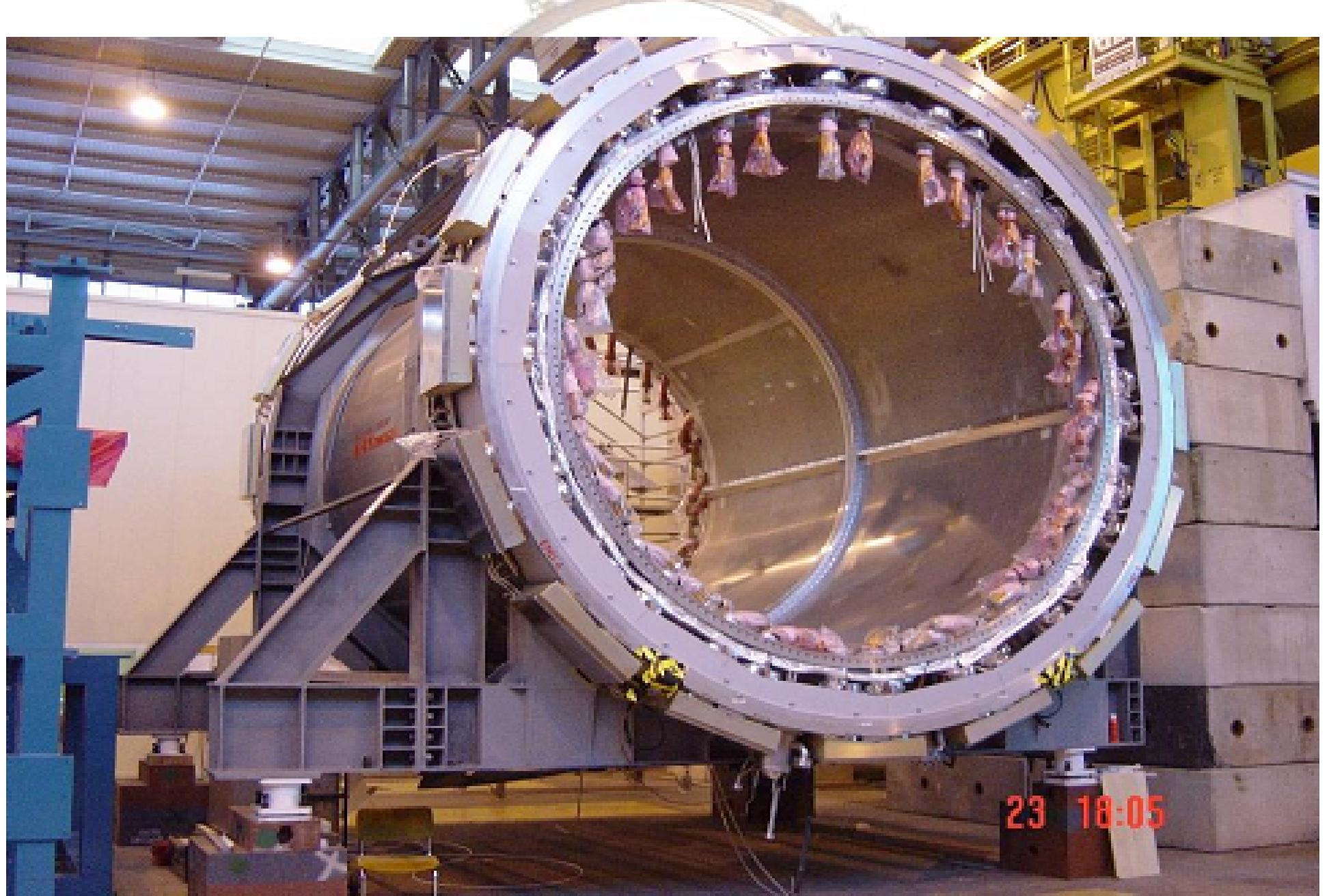
- neutron fluence: $10^{12}/\text{cm}/\text{yr}$
 - total dose: $20\text{Gy}/\text{yr}$



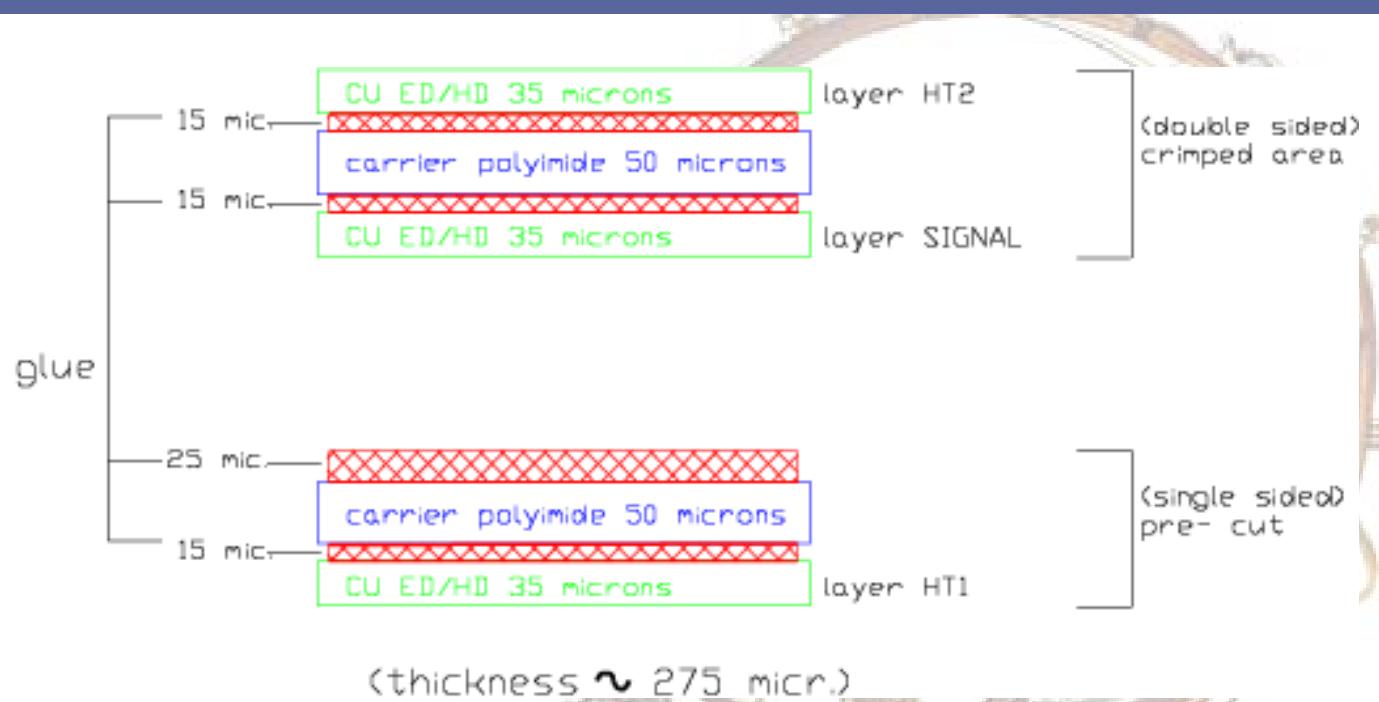
LAr EMB: Cryostat



LAr EMB: Cryostat (2)



LAr EMB: Electrode construct

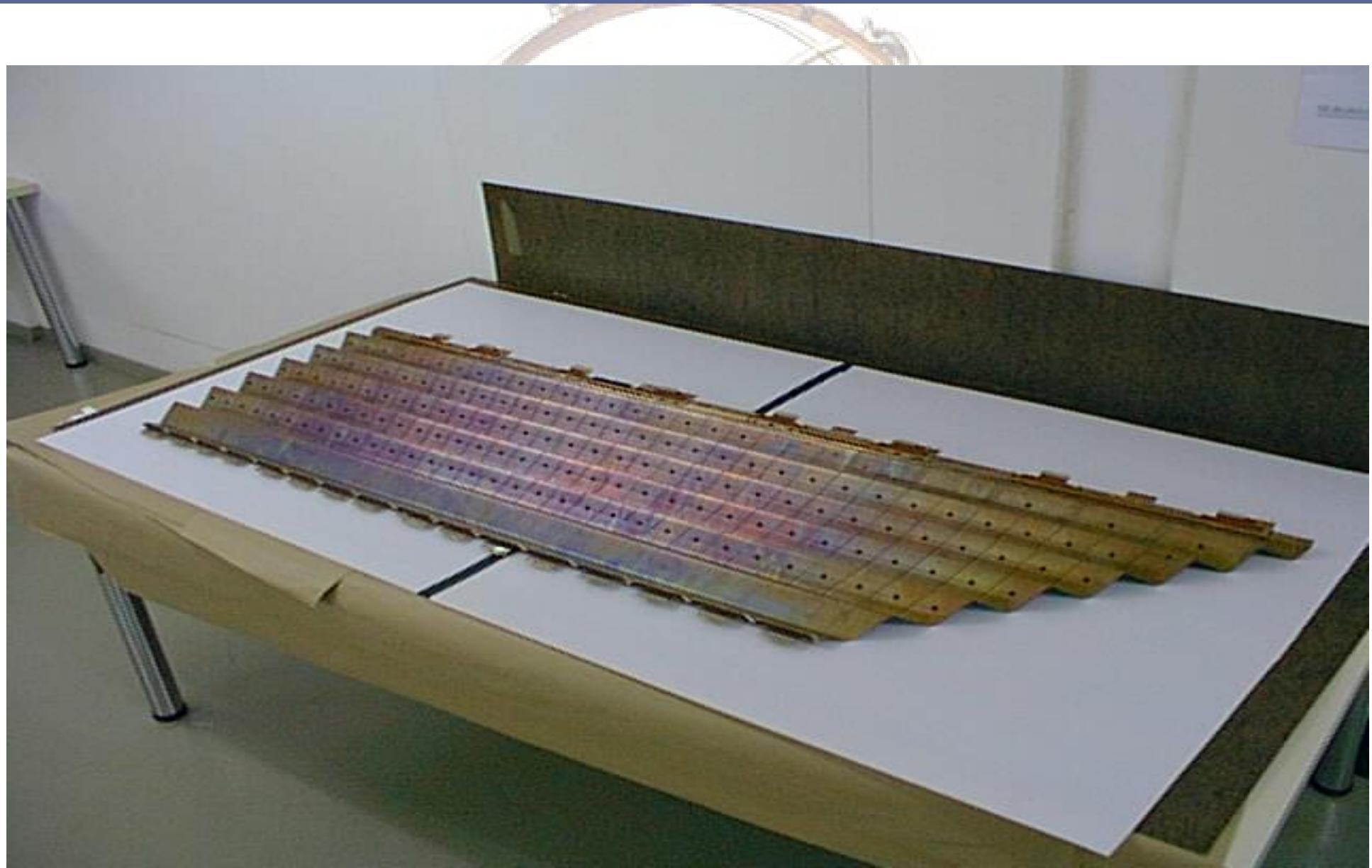


- Etching of the inner layer (signal)
- Bonding
- Etching of the 2 outer layers (HV)
- Tolerances:
 - overall size: 0.4mm
 - accuracy of etching pattern: 0.2mm
 - relative alignment of the 3 layers: 0.2mm
 - clearance between cells: 0.1mm
- Screen printing HV distribution resistors, pads and bridges (*high resistivity ink: $\rho \simeq 1M\Omega/\square$*)
- Connector crimping to extract signals

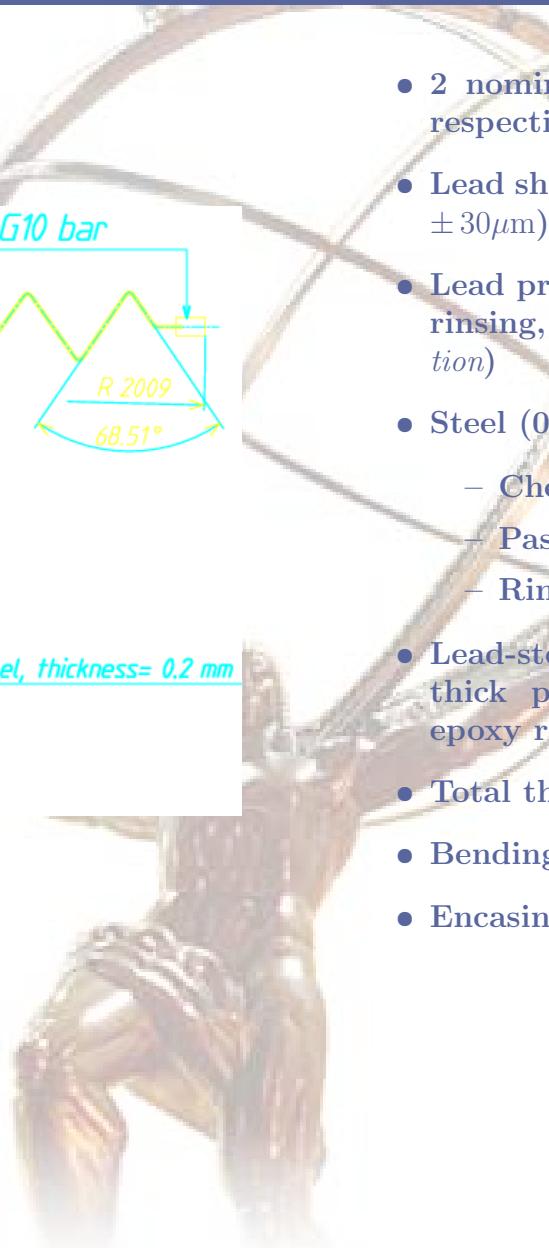
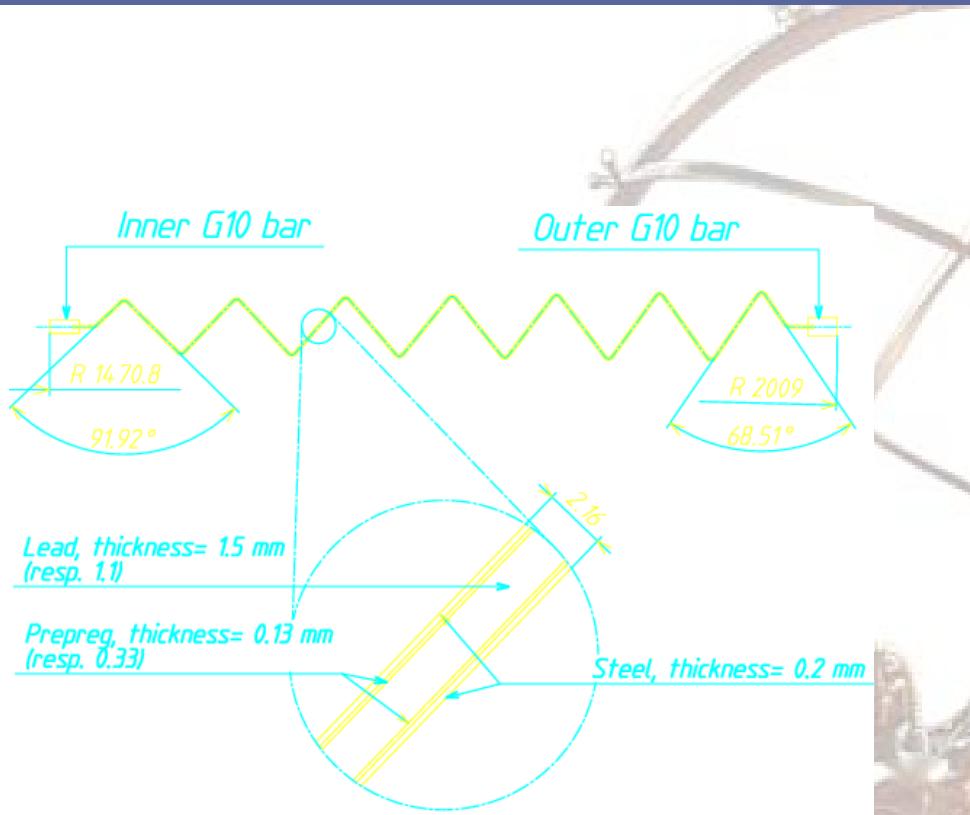
LAr EMB: Kapton Bending



LAr EMB: Kapton Bending (2)



LAr EMB: Absorber preparation

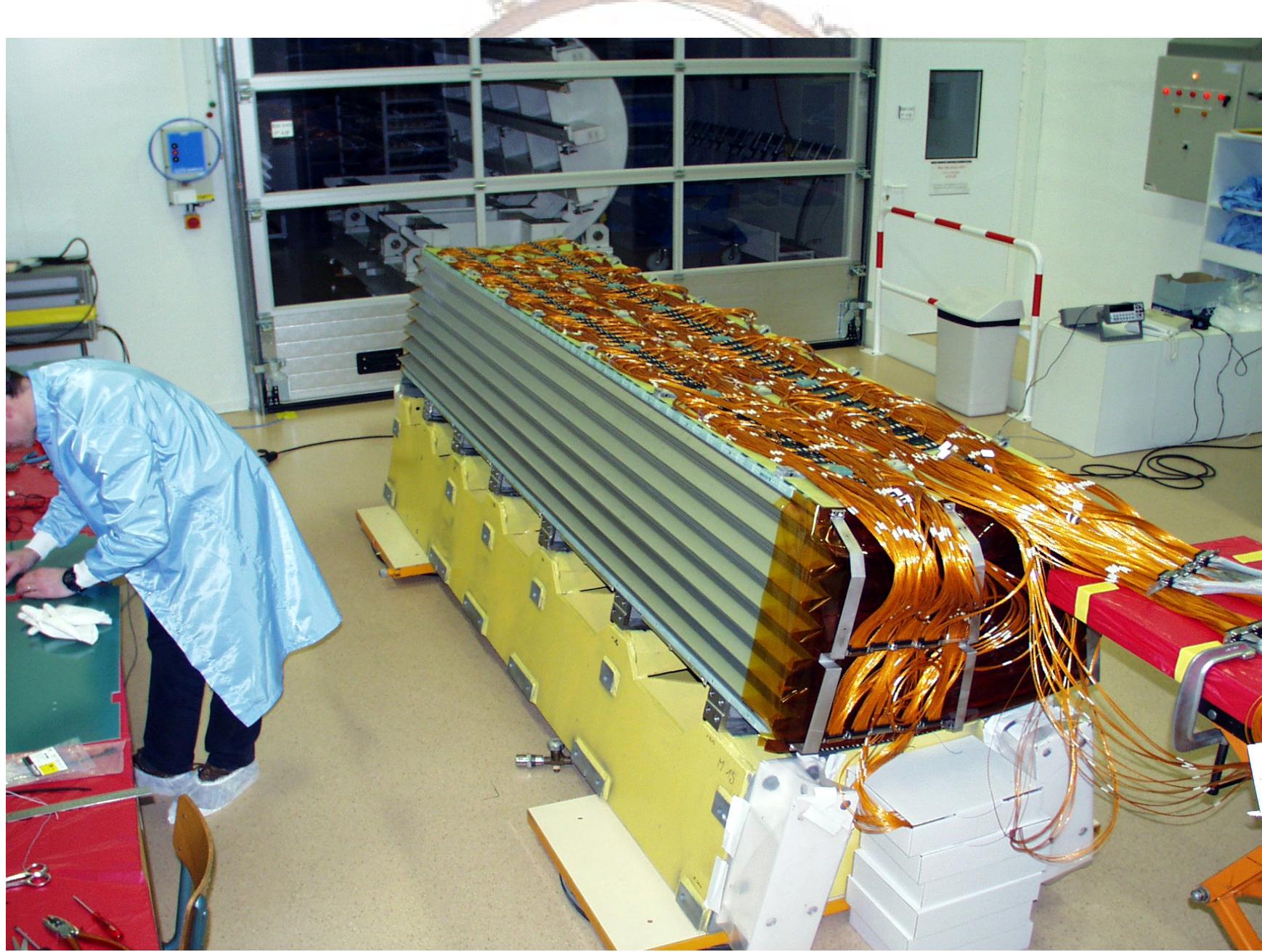


- 2 nominal thicknesses (1.5mm, 1.1mm for $\eta \leq (\geq) 0.8$ respectively)
- Lead sheets: (*Online X-measurements to control flatness. Max. $\pm 30\mu\text{m}$*)
- Lead preparation: water brushing with alumina powder, rinsing, drying (*done just before use because of fast lead oxidation*)
- Steel (0.2mm thick) preparation before gluing:
 - Chemical degreasing (FINOX)
 - Passivation (NETINOX)
 - Rinsing and Drying
- Lead-steel sandwich by gluing with 0.13mm (0.33mm) thick prepreg (fiberglass cloth pre-impregnated with epoxy resin).
- Total thicknesses 2.16mm for both configurations
- Bending
- Encasing in G10 bars to hold in place

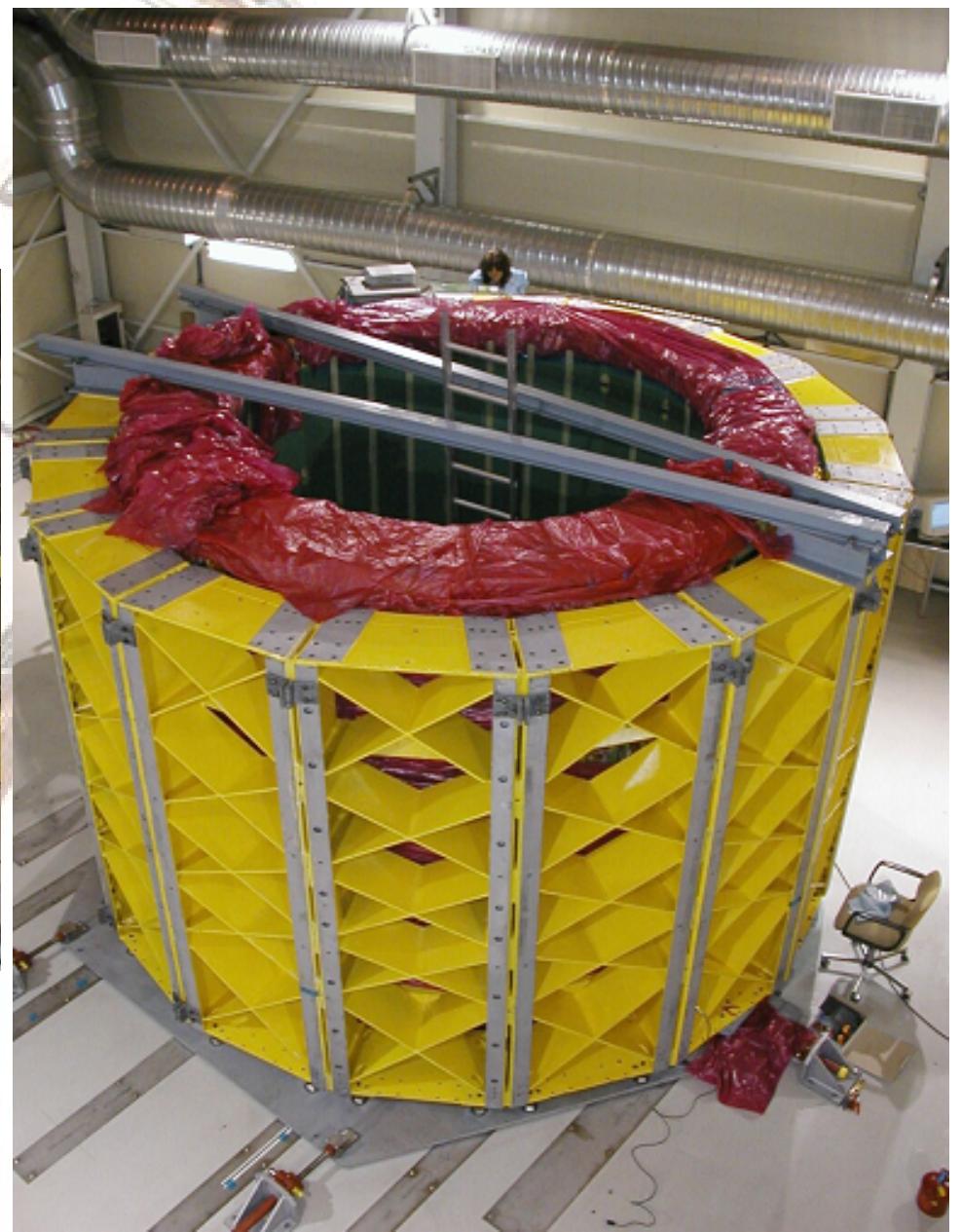
LAr EMB: Stacking



LAr EMB: Cabling



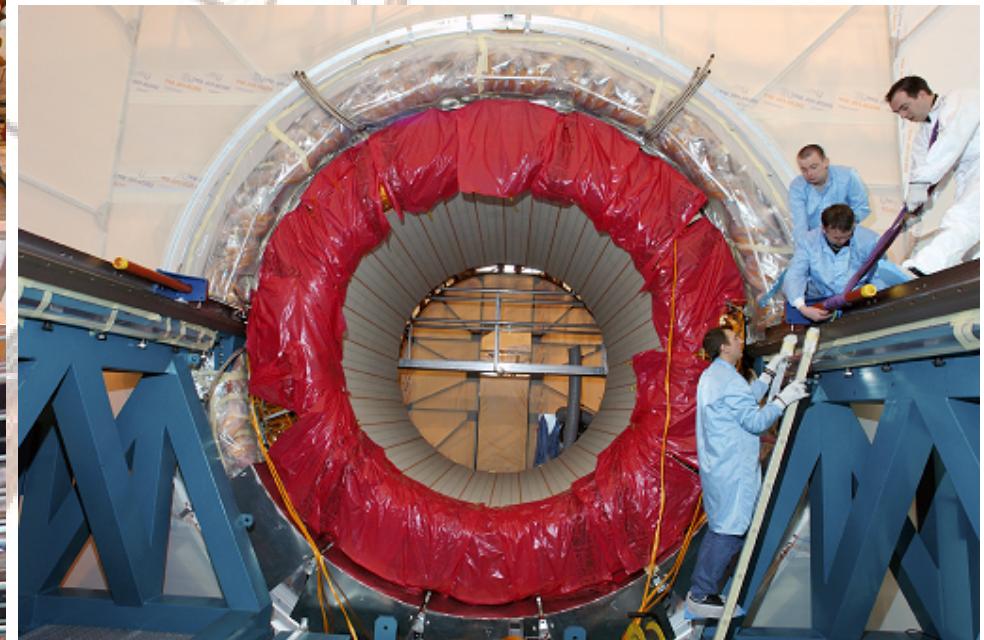
LAr EMB: Wheel Assembly



LAr EMB: Wheel Rotation



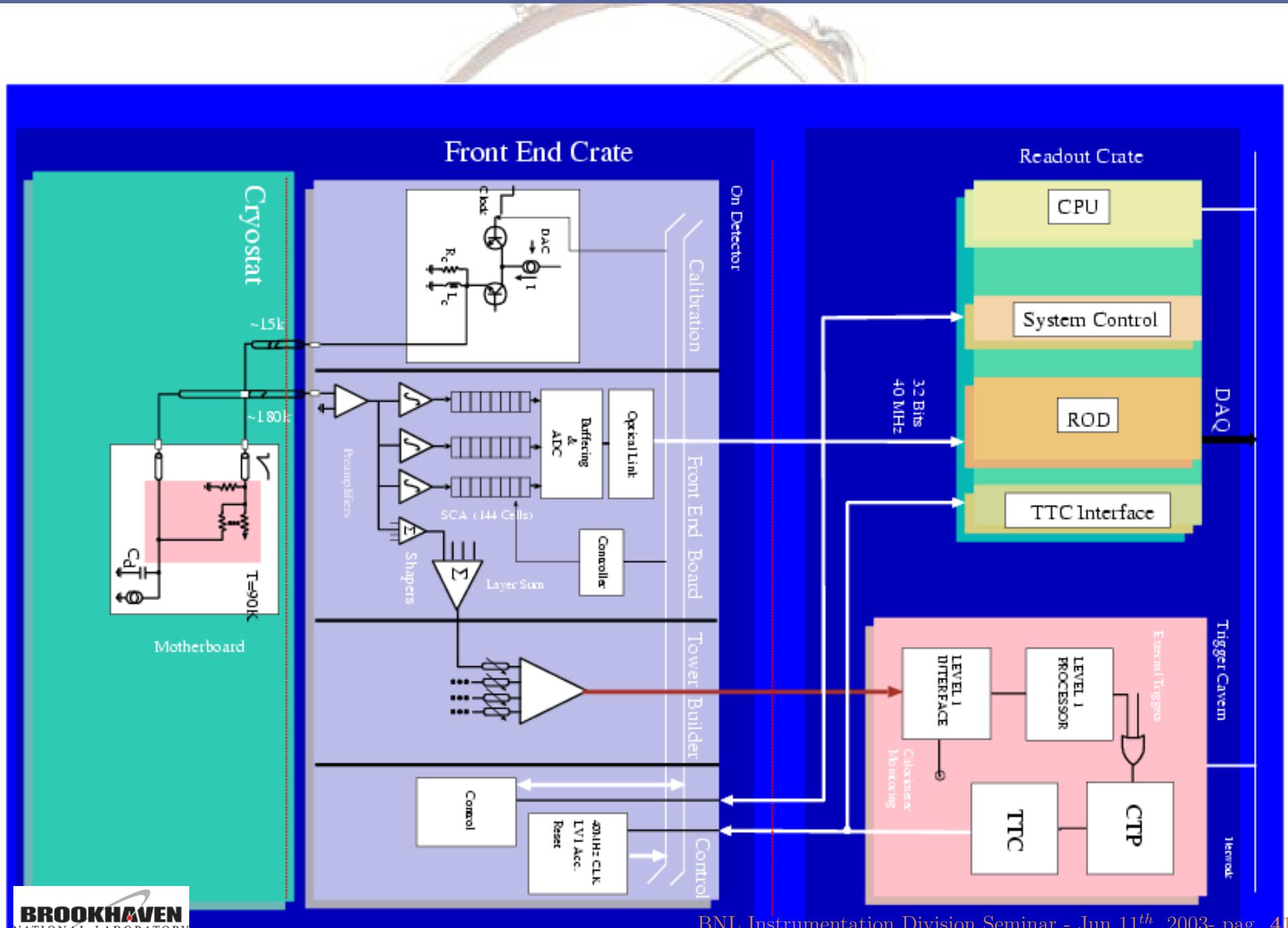
LAr EMB: Insertion



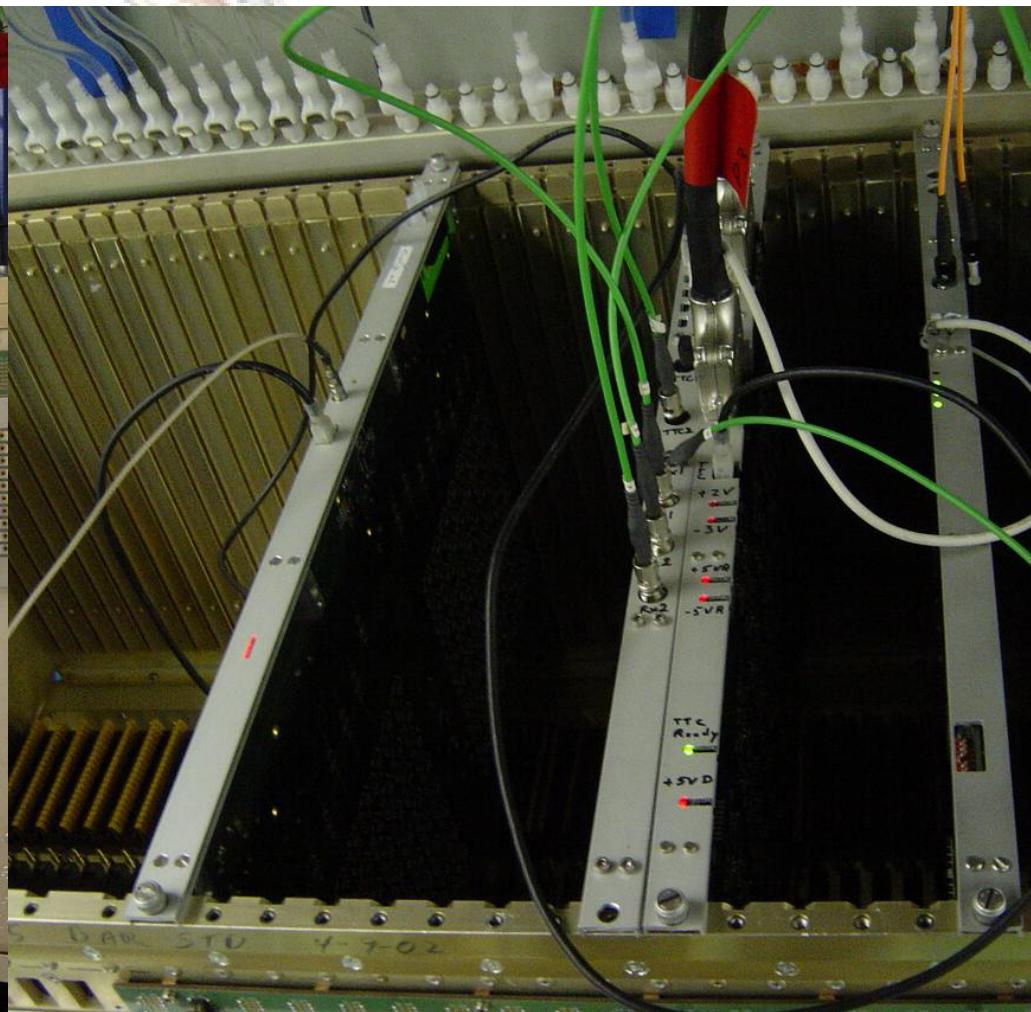
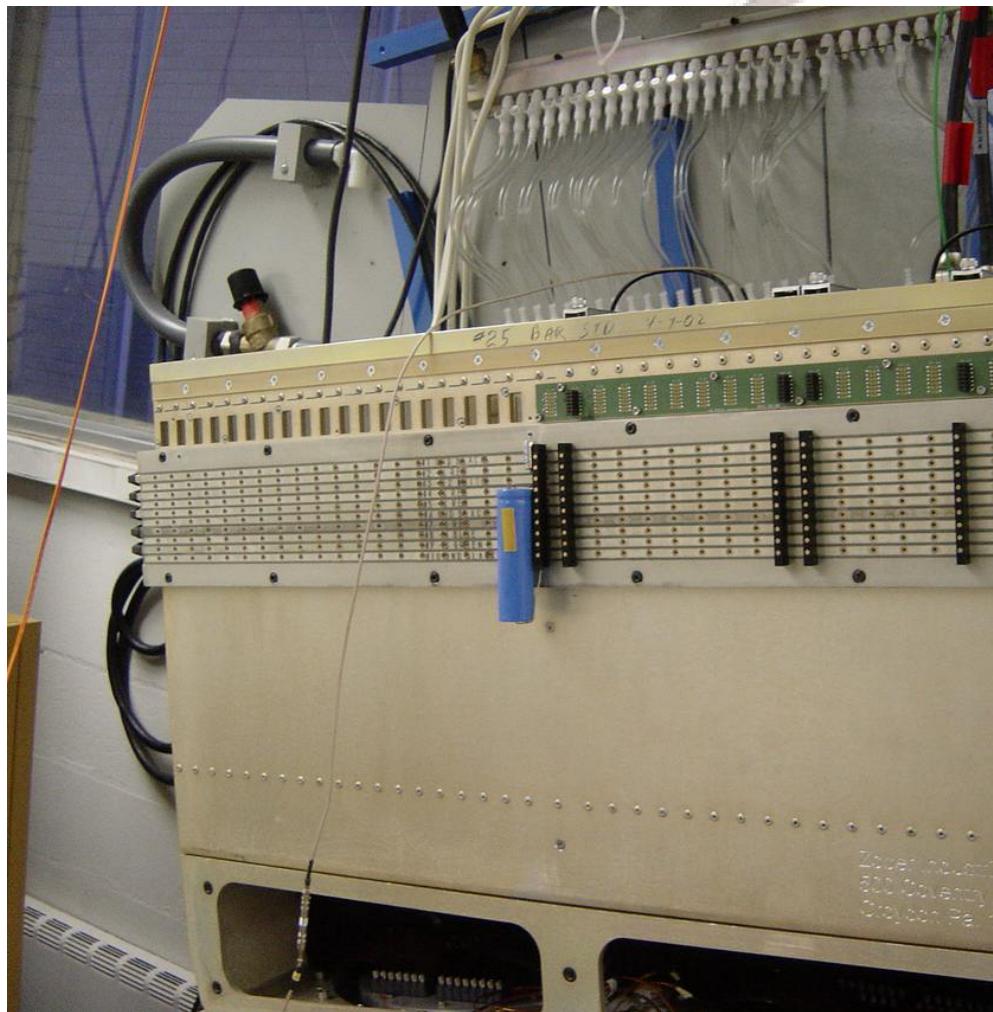
LAr EMB: Readout Architecture



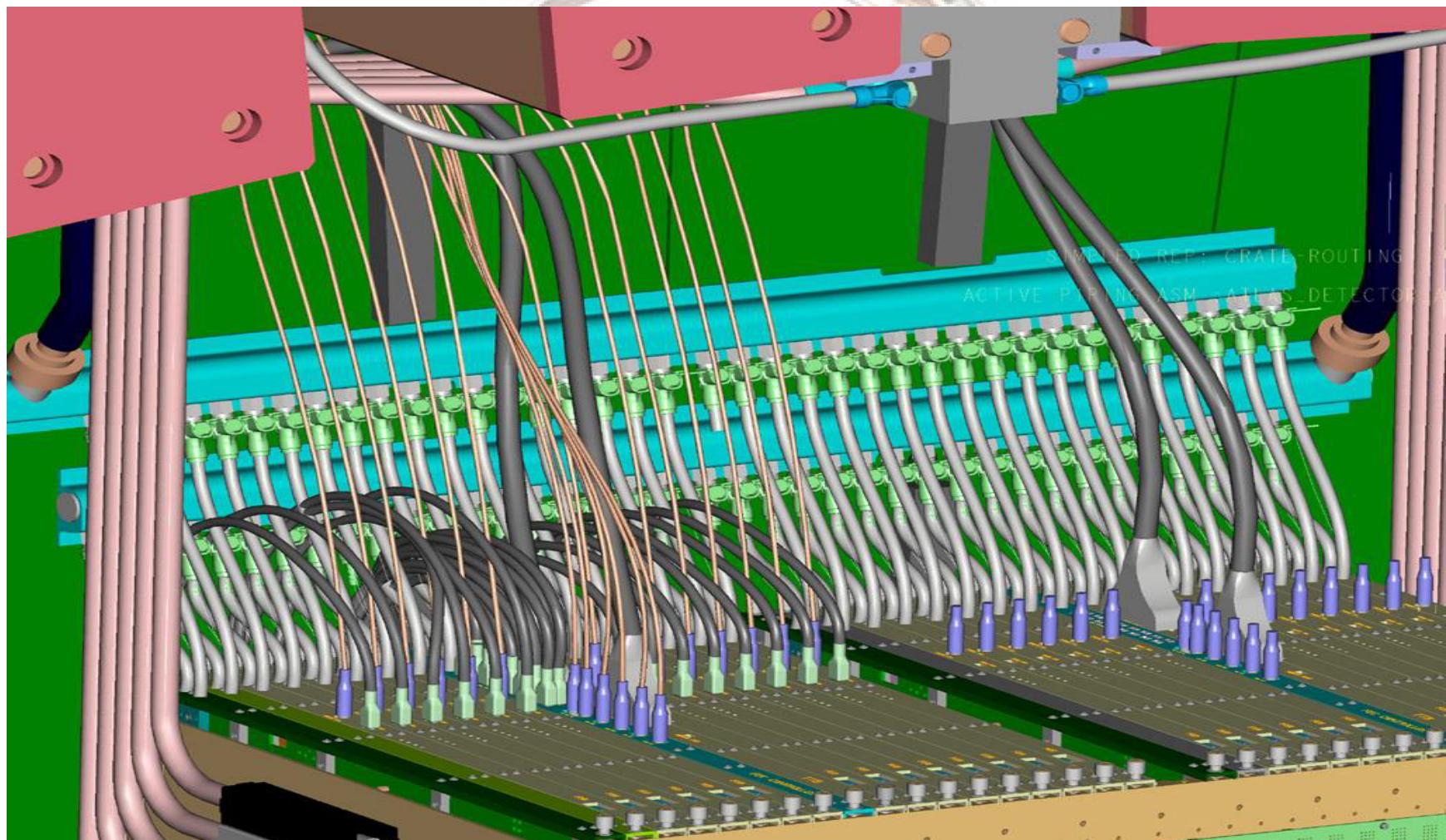
LAr EMB: Readout Architecture



LAr EMB: Front-End Crate

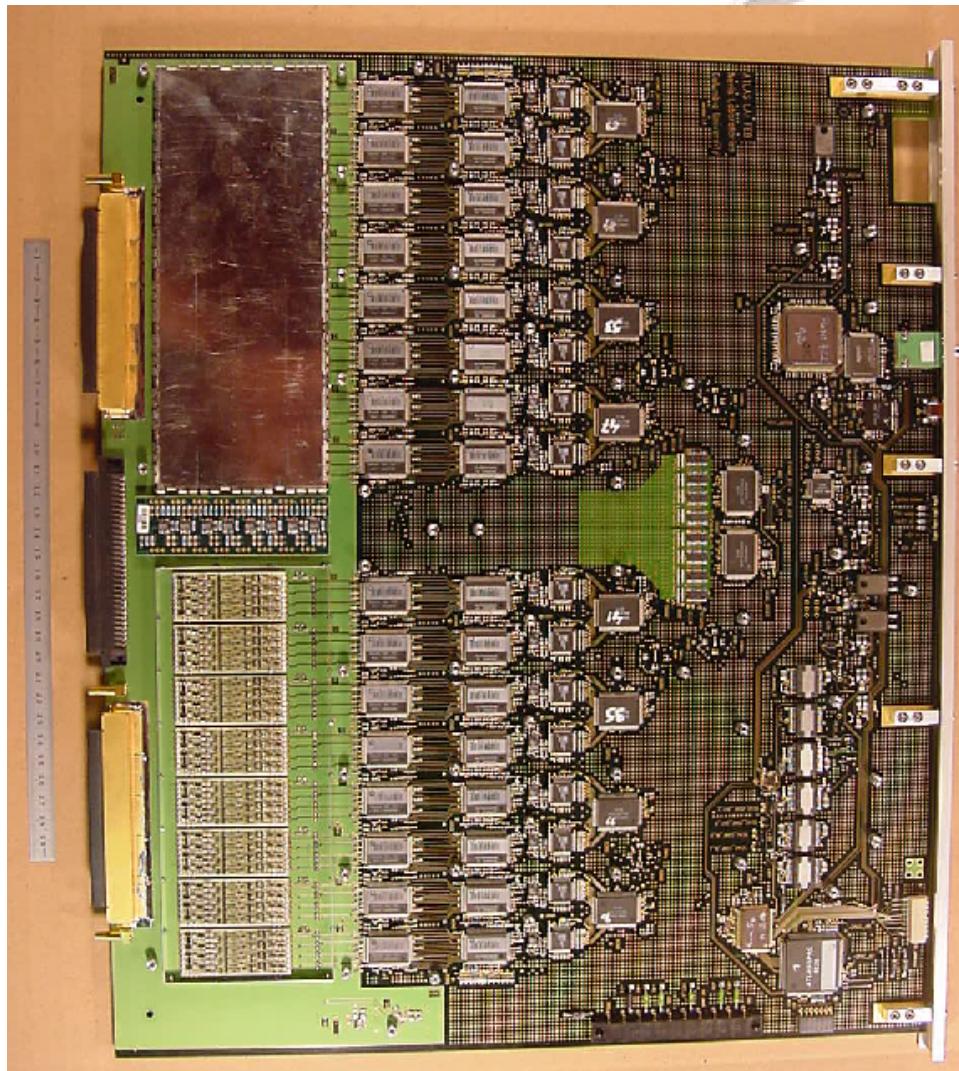


LAr EMB: Front-End Crate (2)



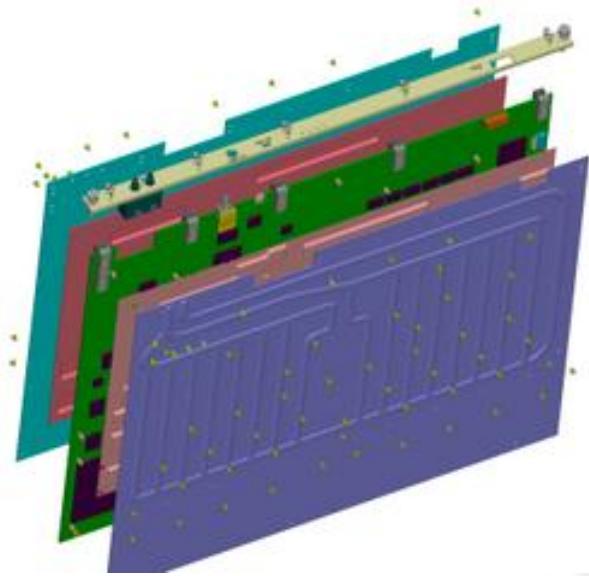
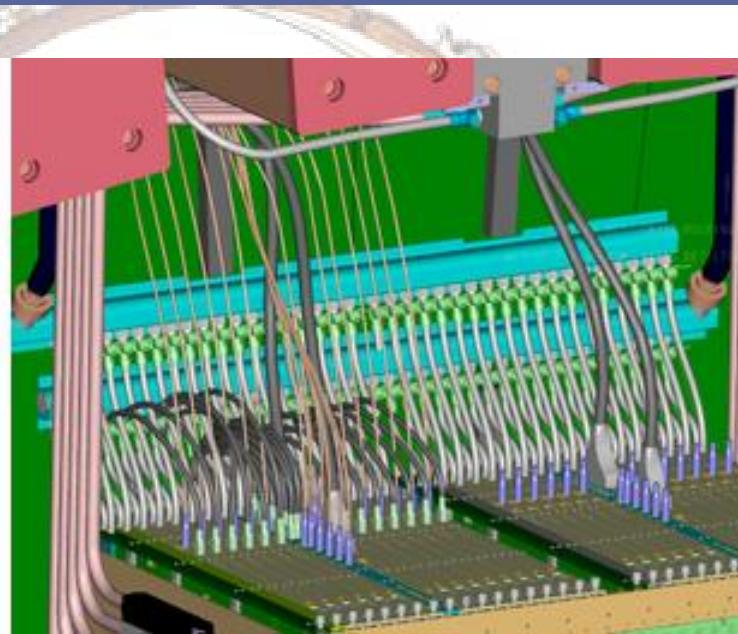
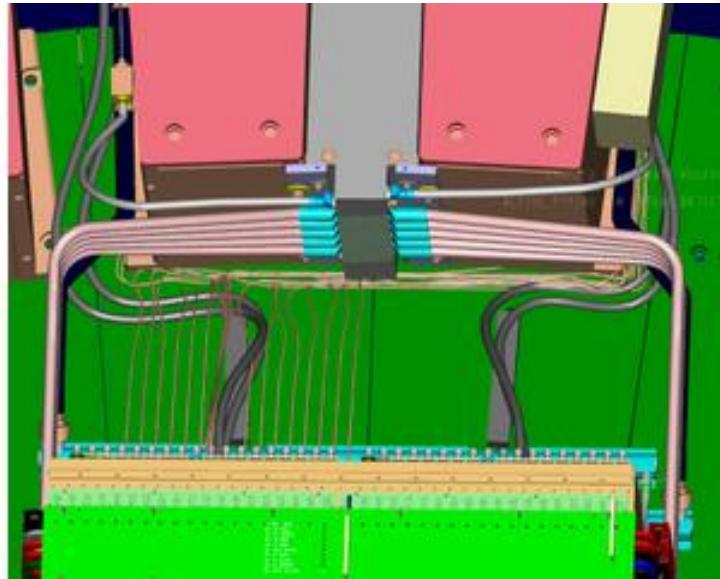
Access space limited during installation. Maintenance and operation is not going to be easy...

LAr EMB: Front-End Board

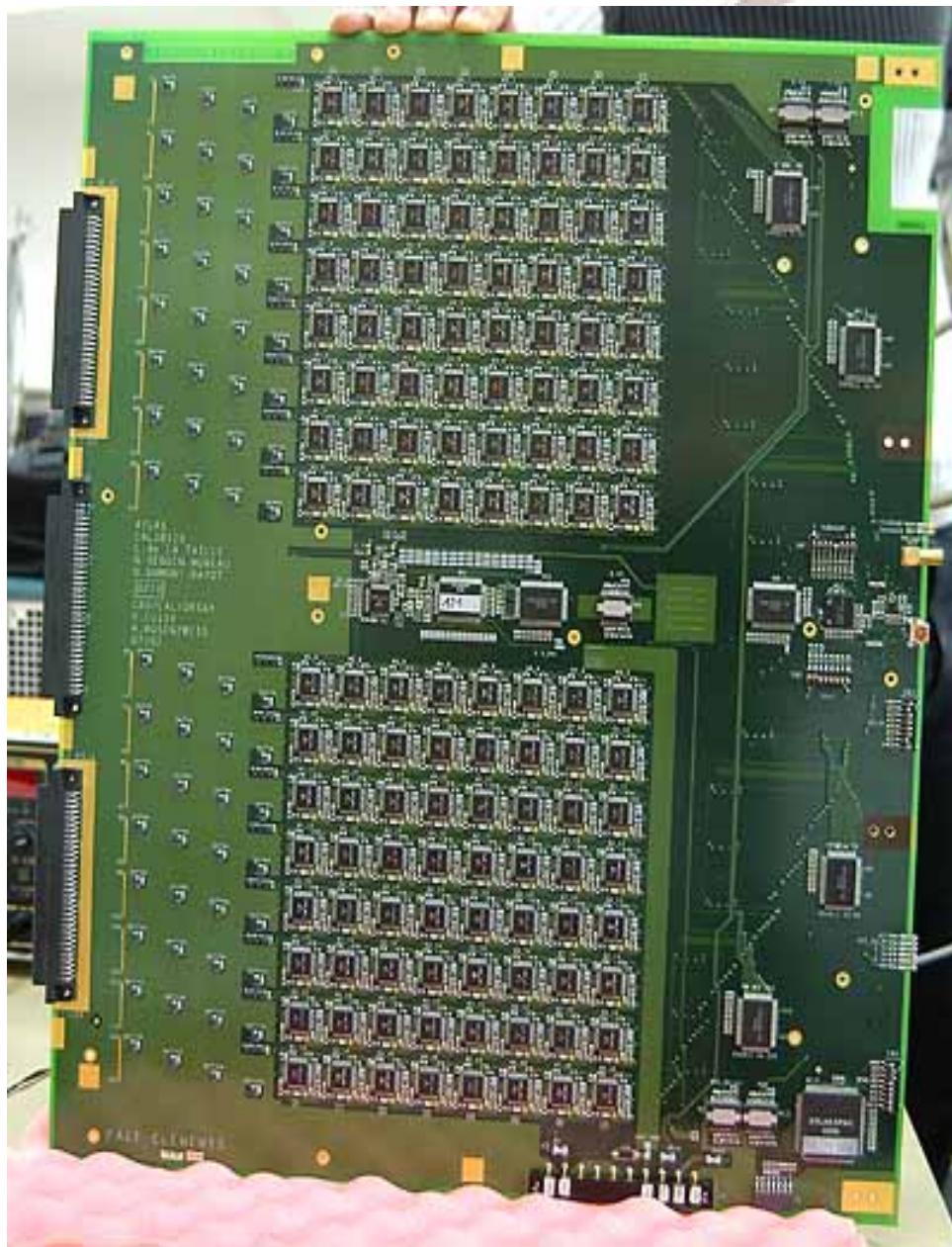


- 32 hybrid (4 preamplifier each) bipolar discrete technology
- 32 shaper (BiCMOS AMS): bipolar $(RC)-(CR)^2$ ($\tau \simeq 13.1\text{ns}$)
 - 4 input channels
 - 3 gain settings (1/10/100) to cover the 16 bit dynamic range needed
 - Integral non-linearity ($\leq 0.2\%$)
- Analog pipeline: 40MHz sampling, SCA store samples during L1 latency
- Upon arrival of a L1 signal a train of samples digitized by 12-bit ADCs
- Gain Selector algorithms guarantee all the samples of a channel and event are digitized using the same gain scale
- Digitized data are serialized and transmitted to the ROD (1.6Gb/s optical link)
- First level of analog summing for the L1 trigger through pluggable Layer Sum Board. Signals sent through the baseplane to the Tower Builder Board
- **Crate fully loaded dissipates 3kW → water cooling (*leakless, i.e. negative pressure circulation system*)**

LAr EMB: Cooling



LAr EMB: Calibration Board

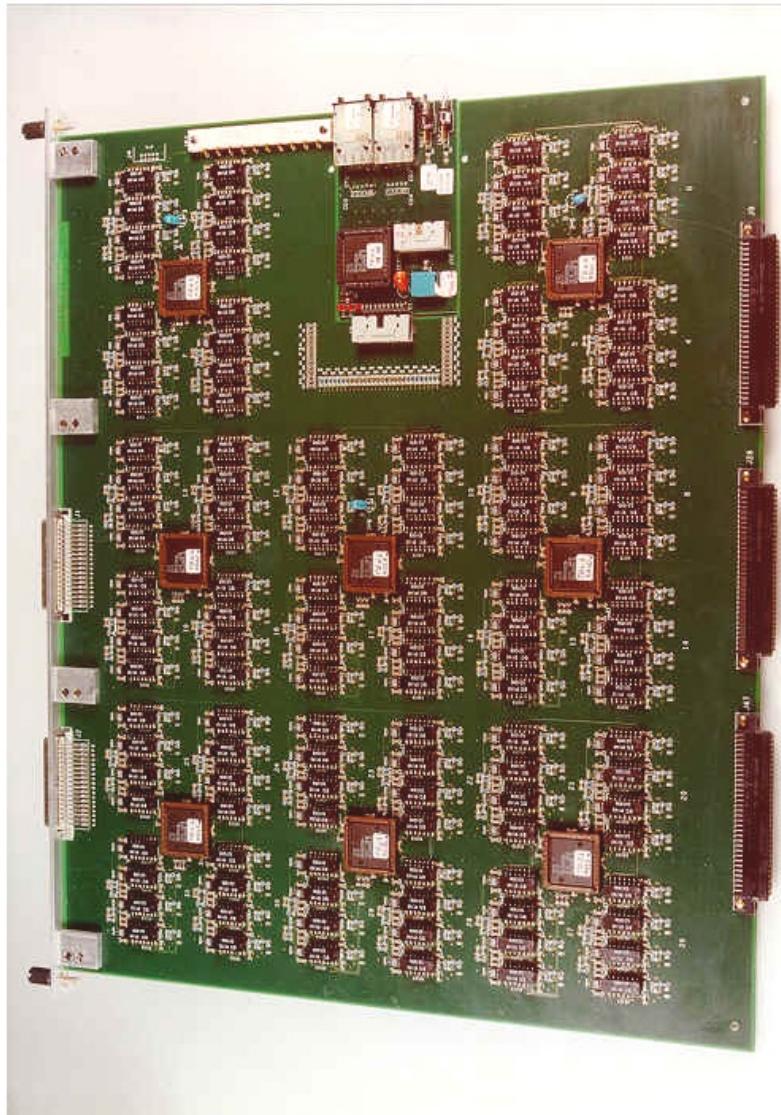


- 128 indep. current pulsers onboard: uniformity $\leq 0.11\%$ (after shaping)
- Programmable through a 17 bit DAC (DMILL technology)
- Pulse generated through switches synchronized to the 40MHz clock
- Exponential shape through an RL circuit ($\tau \simeq 365\text{ns}$)
- DAC voltage converted to DC current through custom static low-offset ($10\mu\text{V}$) operation amplifiers (DMILL technology)
- Control Registers sets calibration patterns, DAC amplitudes and set delay chips to change the relative phase of the pulse with respect to the 40MHz clock

LAr EMB: Tower Builder Board



LAr EMB: Tower Builder Board

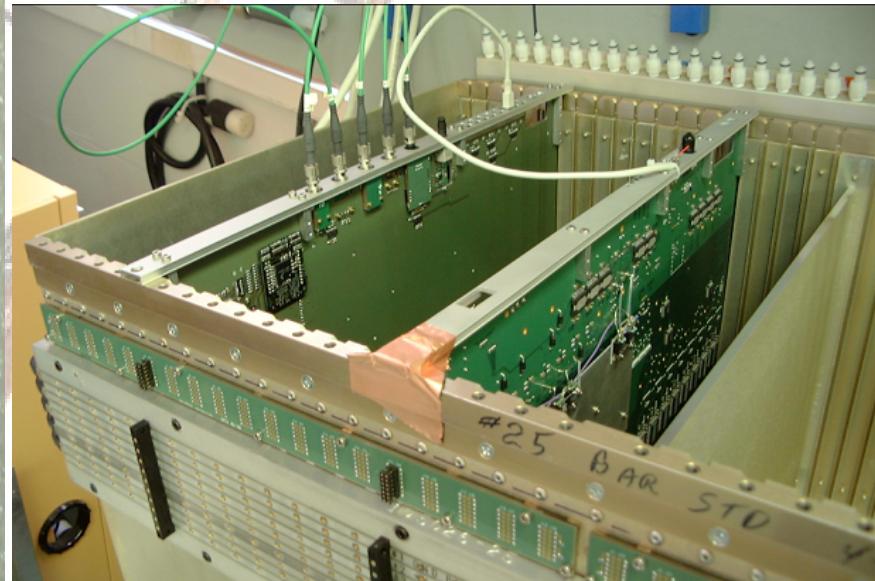


- Analog summing (4 layers in depth) to reconstruct the E_T deposited in a tower
- Tower size are: $\Delta\eta\Delta\phi = 0.1 \times 0.1$ for $\eta \leq 2.5$ ($\Delta\eta\Delta\phi = 0.2 \times 0.2$ for higher η)
- Conversion from deposited energy to E_T :
 - linear mixer gain on the LSB
 - final adjustment in the TBB
- Summing over the layers can be done only after pole zero correction (to compensate for the different t_p due to a wide range of detector capacitance)/ and gain correction.
- Programmable delay settings can optimize the relative phase of the input signals from the different layers
- Signal outputs sent to Trigger Cavern Receiver boards will compensate for the attenuation along the cables (70m).

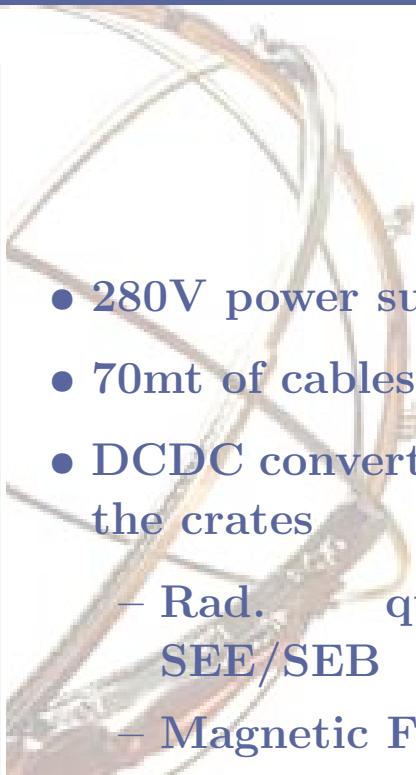
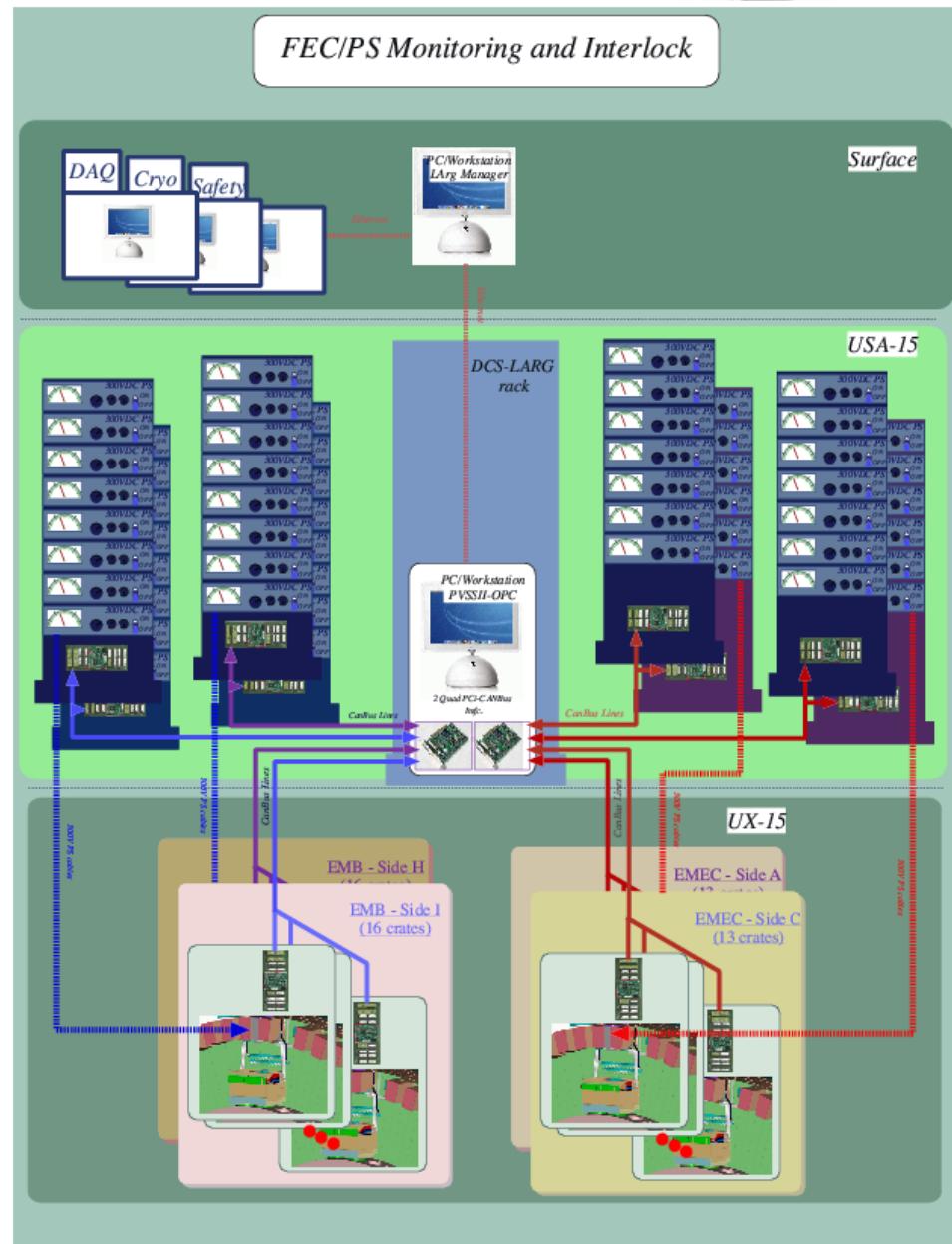
LAr EMB:Controller Board



- Board settings and monitoring (through a custom serial protocol, SPAC)
- Distribution of the Trigger signals

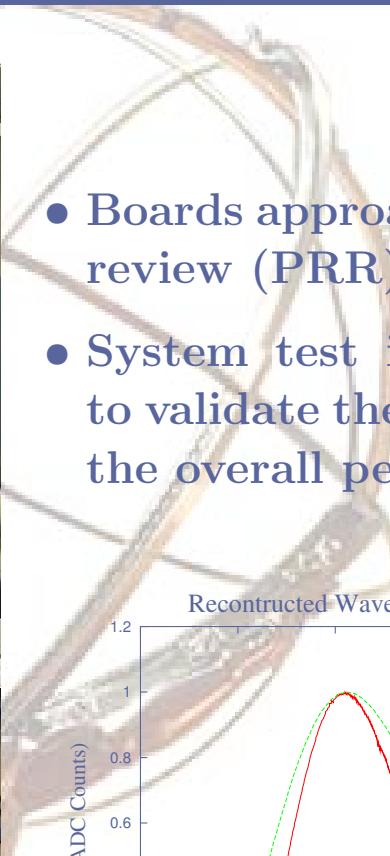


LAr EMB: Power Supply and Monitoring



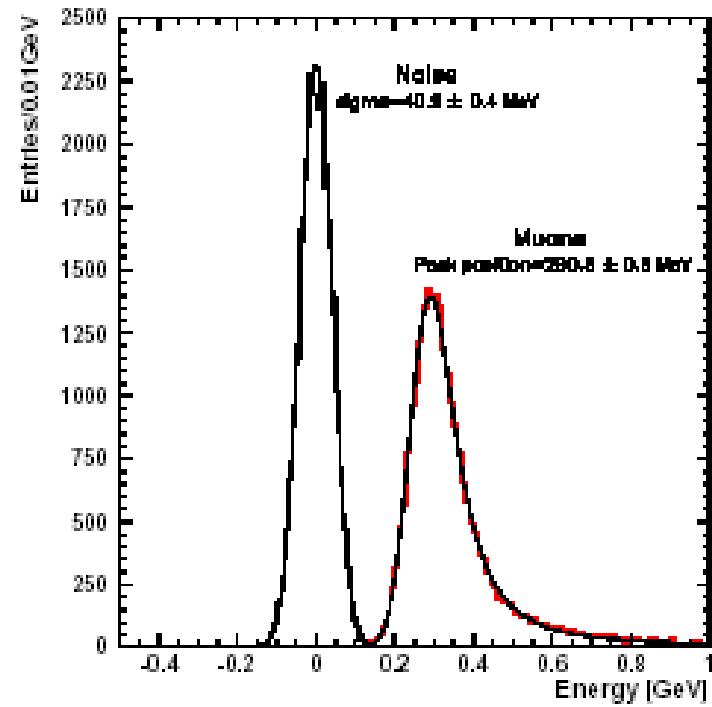
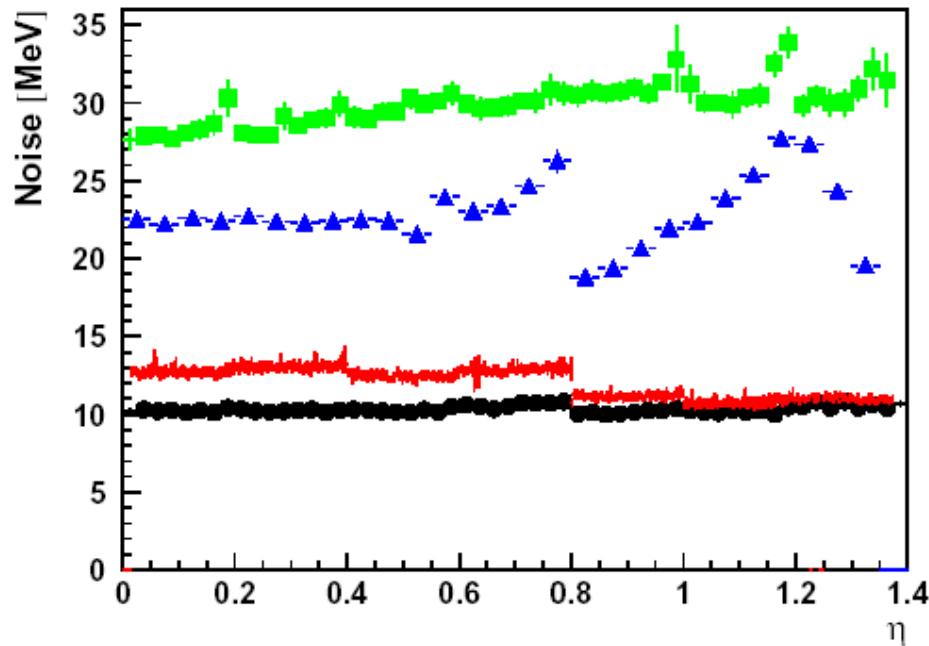
- 280V power supply in USA15
 - 70mt of cables down in the exp. hall
 - DCDC converter installed on the top of the crates
 - Rad. qualification: 300kRad, SEE/SEB
 - Magnetic Field
 - Monitoring of the voltages and of the temperatures through custom *embedded local monitoring board* (ELMB) communicating through CANBus to the main monitoring framework

LAr EMB:FE System Tests

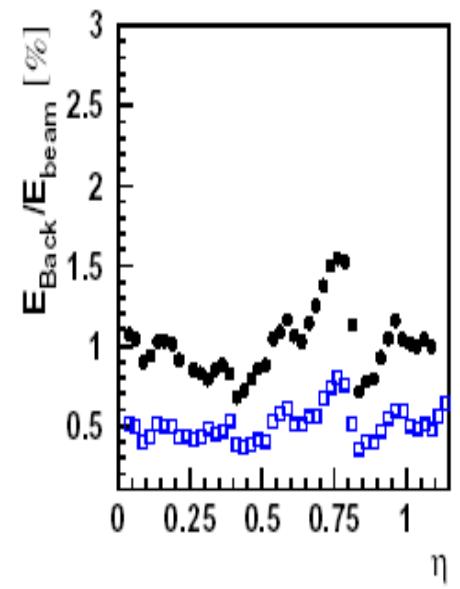
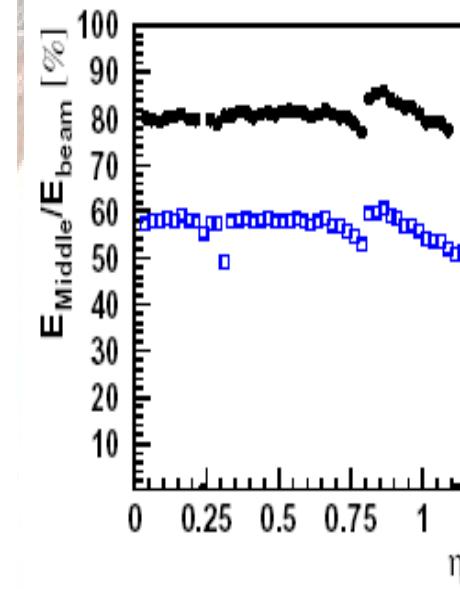
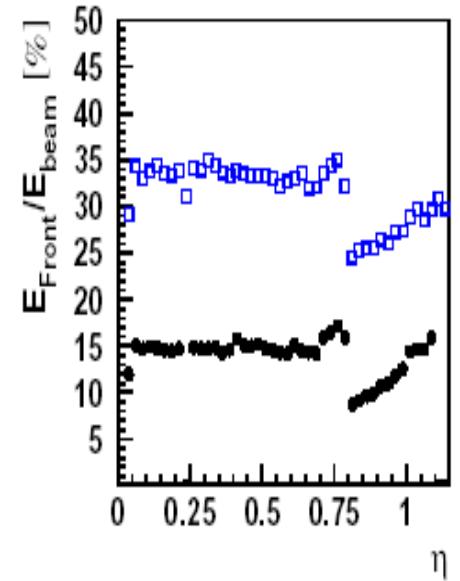
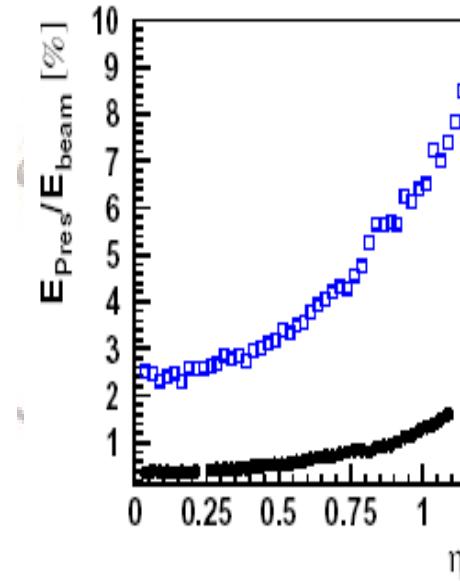
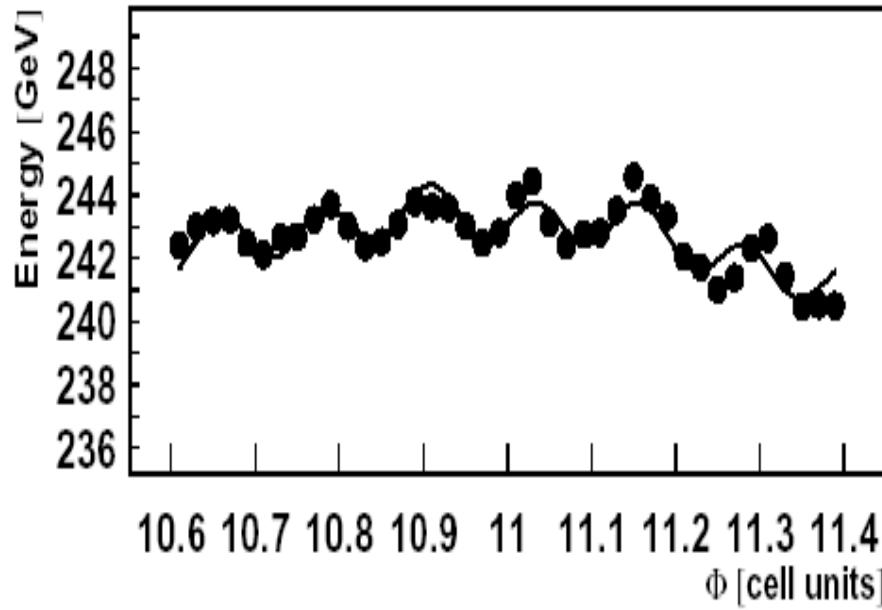
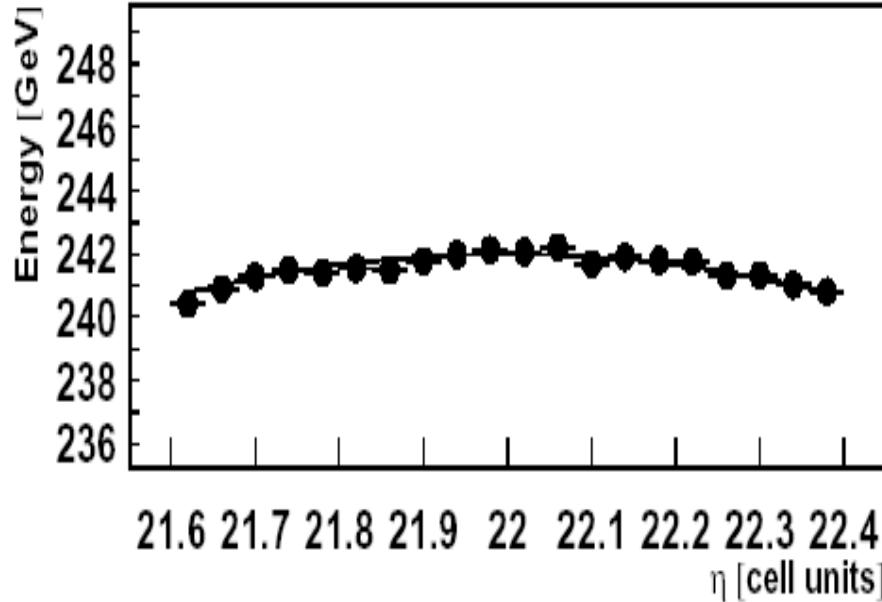


- Boards approaching production: formal review (PRR)
- System test in progress here in BNL to validate the readout architecture and the overall performances as a system

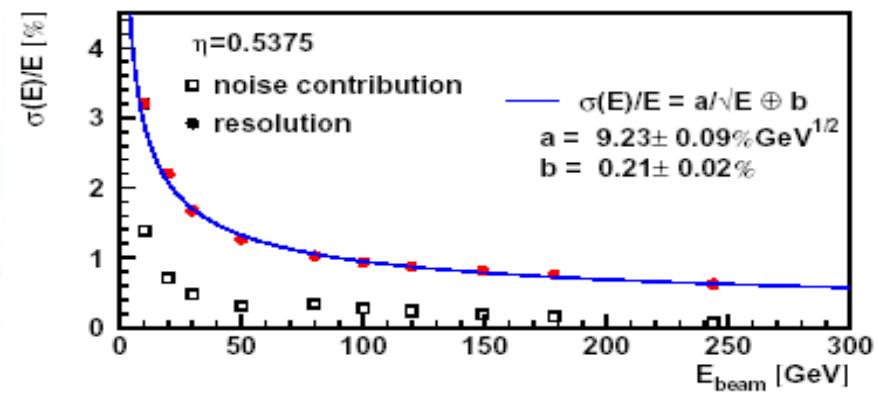
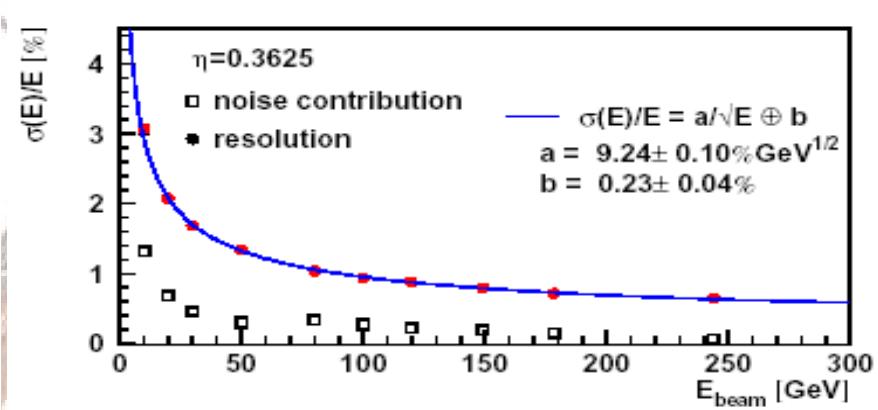
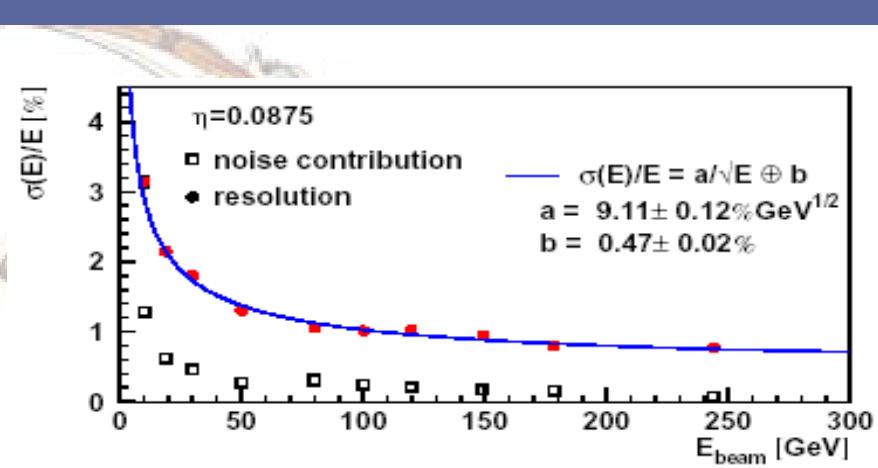
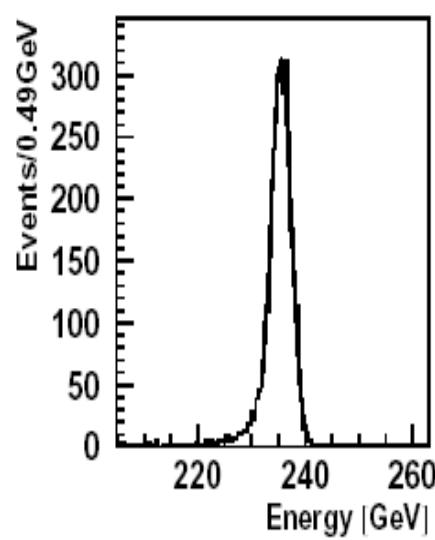
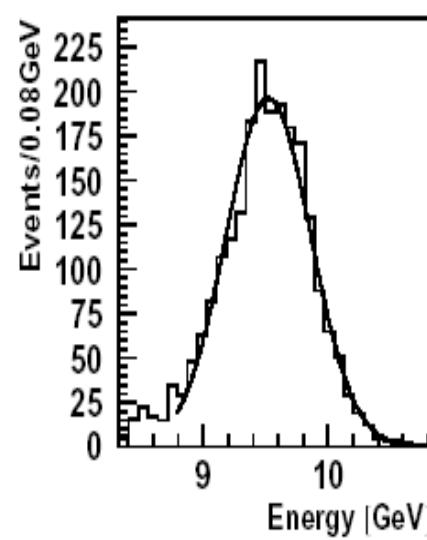
LAr EMB: TestBeam Results



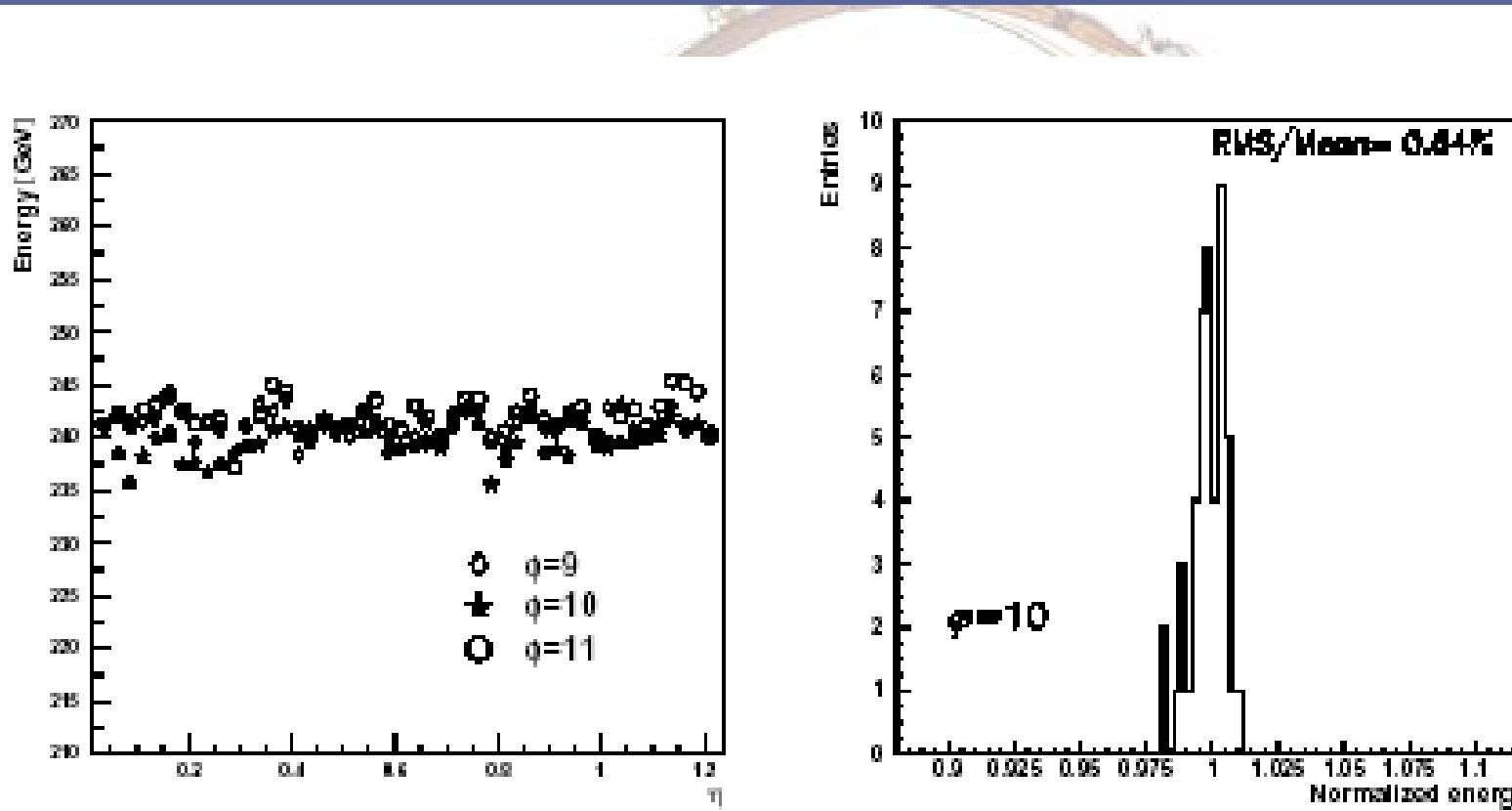
LAr EMB: TestBeam Results (2)



LAr EMB: TestBeam Results (3)



LAr EMB: Problem of Calibrations (4)



- Optimal Filter Coefficient to calculate energy/time

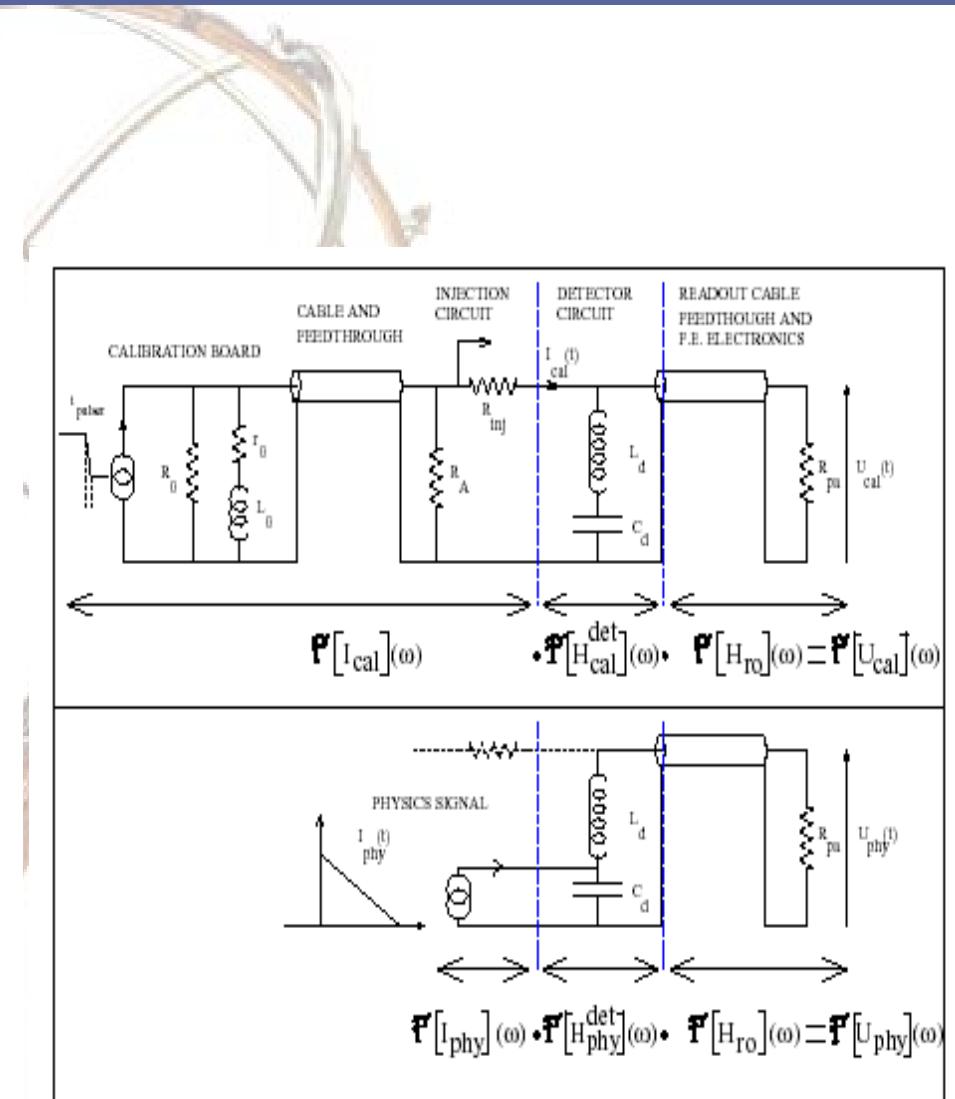
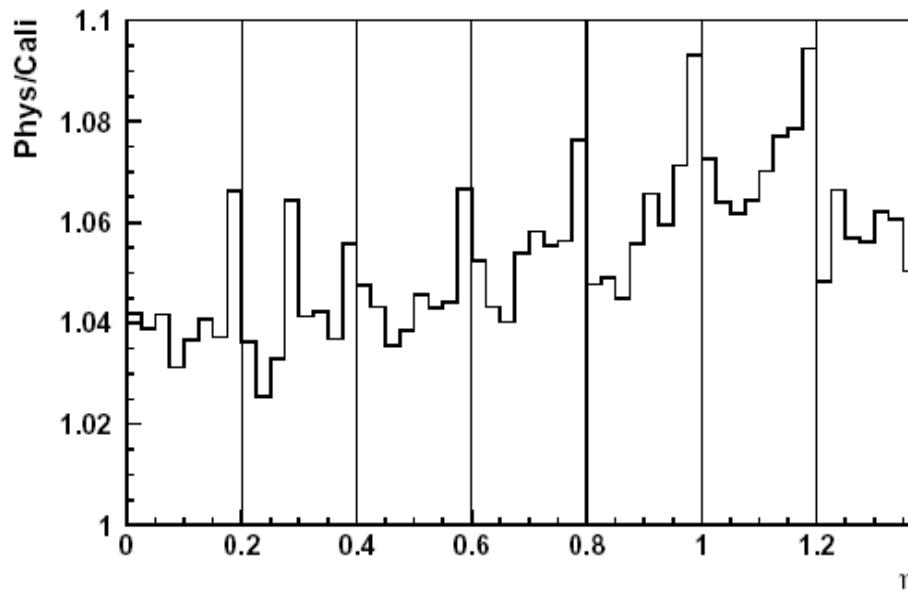
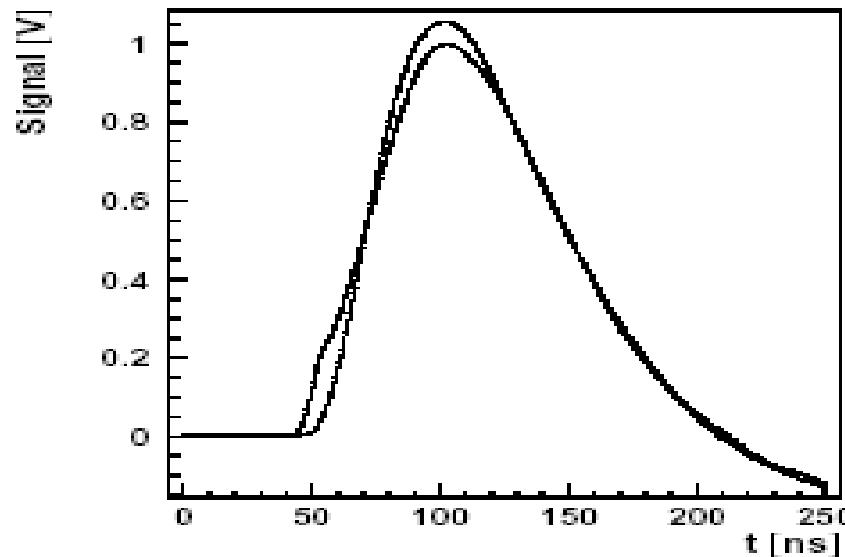
$$E = \sum \alpha_i \cdot (S_i - p) \quad E\tau = \sum \beta_i \cdot (S_i - p) \quad (1)$$

$$\alpha = \frac{\mathbf{A}^{-1} \cdot \mathbf{g}}{\mathbf{G}} \quad \mathbf{G} = \mathbf{g}^T \mathbf{A}^{-1} \mathbf{g} \quad (2)$$

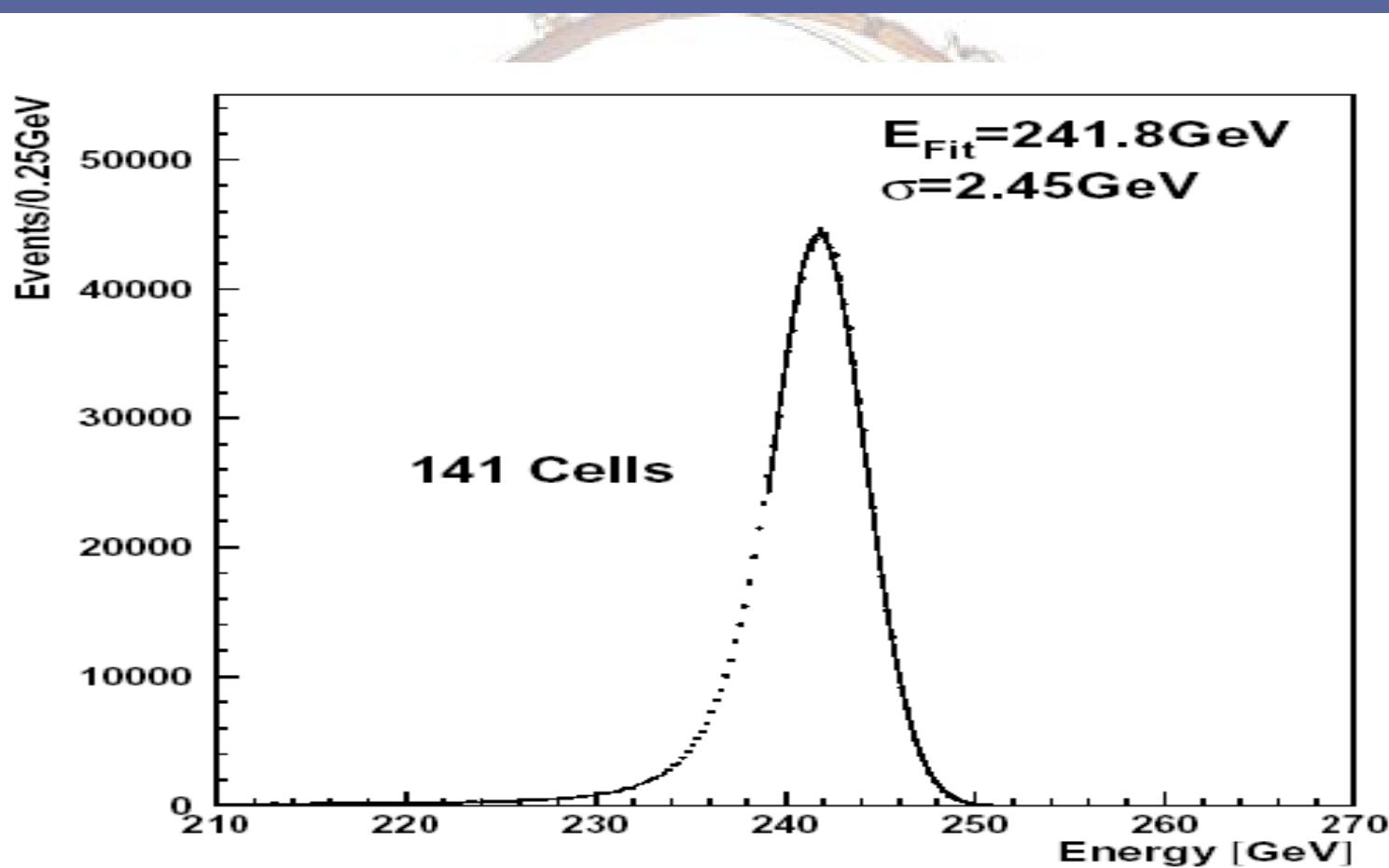
$$\mathbf{g} = \mathbf{h} \star \mathbf{i}_{DET} \quad (3)$$

- Pb.: Correct extraction of the detector response from calibration

LAr EMB: TestBeam Results (5)



LAr EMB: TestBeam Results (6)



- 1M events
- Equivalent to $\Delta\eta \times \Delta\phi = 1.2 \times 0.075$
- Unfolding of the constant term: 0.78%